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NATIONAL SEVERE STORMS PROJECT

REPORT No. 12

Analysis of the Severe Weather Factor in Automatic Control of Air Route Traffic

by
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A report on research conducted under contract Cwb-10110 between the U. S. Weather Bureau and United Air Lines, Inc.

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CONTENTS

ANALYSIS OF THE SEVERE WEATHER FACTOR IN AUTOMATIC CONTROL OF AIR ROUTE TRAFFIC*

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ABSTRACT

Two severe squall line cases have been studied, using radar, aircraft, upper air and surface data collected by the National Severe Storms Project. The weather effects of these two cases on the control of air traffic, have been analyzed, using logs of taped conversations received in two Air Route Traffic Control Centers.

Confirmation of the thunderstorm echo features from a WSR-57 radar are good when checked against photographs and flight logs of research aircraft flying various patterns around the storms. One flight involves a supersonic penetration of a strong buildup.

Verification of related forecasts are made from scope data. Most of the important developments fell within the forecasted areas, but the areas designated are too large to be of operational use except for preliminary planning. The short range forecast required in the traffic control computer now envisioned can best be satisfied by sequenced radar echo data measured with a variable gain control. Other methods of acquiring the severe weather measurements for computer input have been evaluated and fall short of the capabilities provided by ground radar.

Recommendations have been made which designate the lines along which research should be extended for increasing our knowledge of thunderstorm dynamics and, more specifically, for improving forecasting techniques.

I. INTRODUCTION

The complexities of the problem of controlling airspace traffic are well understood by aviation in general, and the air carriers in particular. The Federal Aviation Agency, charged with the responsibility of providing the necessary control of traffic to insure safety of operation of all aviation in this country, has been faced with mounting tasks paralleling the rapid growth of air traffic. These tasks were compounded with the injection of turbojet operations into the air traffic picture. The obvious solution to providing the kind of control expected by the flying public is to utilize electronic computers to a higher degree.

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Development of the optimum system has been under way for several years and many resources are devoted to its ultimate design.

Among other factors that must be considered as input data for automatic air traffic control computers are the enroute meteorological parameters. One which affects the safety and comfort of flight to a high degree is the line thunderstorm development that can occupy an appreciable amount of important airspace during the busy season for air travel.

As another facet of research being conducted by the United States Weather Bureau, the National Severe Storms Project provides a source of data well suited to the study of severe storm dimensions and how air traffic control is affected thereby.

This is a report on the findings of a research task conducted for the Weather Bureau as a step toward resolving the severe weather aspects of the aircraft traffic control problem.

II. RESEARCH OBJECTIVES

The broad purpose of the research is to investigate squall lines and other severe weather situations with the aim of developing methods of measuring and evaluating severe weather airspace for coding and transmission to automatic aircraft traffic control systems.

More specifically the studies are to reach objectives along the following lines:

A. Evaluate the accuracy of ground radar presentations on squall line locations, using pilot reports, airborne radar, and other sources of data already available or to be provided by the NSSP.

B. Evaluate the limitations of present radar networks in providing complete coverage of regions in the United States most susceptible to severe thunderstorm activity.

C. Make tentative recommendations on the magnitude of tolerances required in both time and space to insure safe conduct of flights through, around, or over squall lines without the necessity of establishing overly generous airspace blocks.

D. Study present radar methods used by government and civil agencies in defining in three dimensions the zones occupied by squall line developments.

E. Evaluate the feasibility of utilizing surface observations and other data sources as a substitute for, or a supplement to the normal ground radar data.

F. Determine the requirements for forecasts of squall line activity for preliminary alert or planning purposes.

G. Recommend approaches to developing methods of coding in digital form, the meteorological parameters required for input to computers in setting up airspace weather blocks.

In pursuing the above objectives, two case studies of major squall lines have been incorporated. These two cases provide extensive aircraft, surface, and rawinsonde data. The collection of all available information on air traffic present in the affected area during the two events will be related to weather deviations in flight plans.

Deficiencies in forecasting and communications are summarized and conclusions reached as to how the handling of traffic control might be improved with refinements in techniques centered around the severe weather.

III. DATA SOURCES AND PRESENTATION

The two case studies concern the severe squall lines which occurred on May 4 and May 5, 1961, in Oklahoma, Kansas, and Texas. On these two dates the specially instrumented aircraft of the National Severe Storms Project were deployed in data collection for the affected area. Ground radars centered about Oklahoma City were operated for the specific study of these events and the surface observation and radiosonde networks were implemented in coordinated support of the investigations. The complete organization of the NSSP is described in reference [1].

Traffic control information on aircraft operating during these two periods in the storm area were obtained from tape recorder playbacks logged in the FAA Air Route Traffic Control Centers at Kansas City and St. Louis. Analyses of the meteorological and air traffic pictures are presented in Sections IV and V. These are focused on the radar presentations approximately 1 hour apart as depicted by the Weather Bureau's WSR-57 radar located at Will Rogers Airport in Oklahoma City. Surface analyses are those made by NSSP current with the field operations. Being based only on hourly teletype reports, they are not to be construed as mesoanalyses. Research flight data are timed to the particular radar analysis, where available. Not all of the logged contacts from the two ARTC centers are presented, but selections have been made where weather played a role in the control or operation of the flight, either by inference or by direct reference.

A. RADAR DATA

The WSR-57 10-cm. radar at OKC is usually operated at the maximum range of 250 miles. When severe thunderstorms have moved to within 100 miles of the site, the radar is used operationally for the public forecast and warning service responsibility of the Weather Bureau.

This radar is used for PPI presentation only. Intensity of the echo is determined by the step receiver gain reduction capability of the set. Attenuation can be controlled from 0 to 42 decibels in 7 steps of 6 db. A sample frame of the 35-mm. film of the PPI picture is shown in figure A.

Echo patterns reproduced in this report are from direct tracings of film frames projected on a microfilm viewer. The viewer was adjusted for a scale size corresponding to the scale of the map base.

Copies of film from the other coordinated radars in use at OKC with RHI capabilities were not available for this study. However, logs from the radar room tapes referring to vertical dimensions of echoes are used in this analysis. Where logged data from ARTC centers were outside the 250-mi. range of the OKC radar, the SD-1 radar report summaries were used in lieu of the radar film.

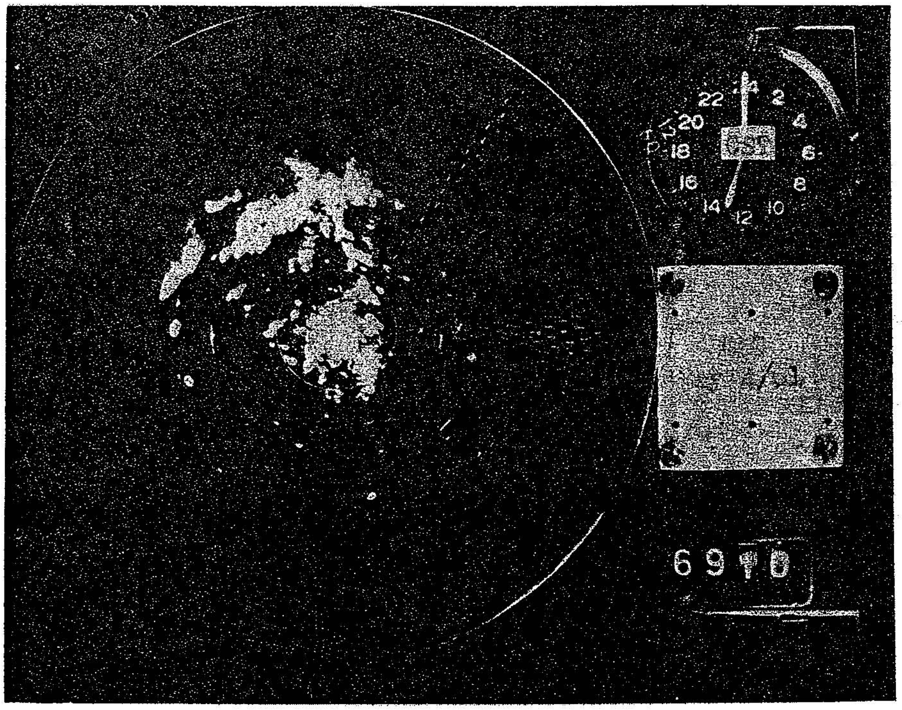

Figure A.- Copy of 35-mm. film frame from Weather Bureau WSR-57 radar scope at Will Rogers Field, Oklahoma City. Each frame contains information on gain and antenna setting, range and pulse length. Speckle pattern in this photograph is probably from interference with 10-cm. radar aboard DC-6 research aircraft 100 miles west of the airport. (See fig. 7 for enlargement of this 250-mi. scope display.)

B. NSSP AIRCRAFT DATA

The instrumented aircraft flown on the NSSP missions of May 4 and 5, 1961, accumulated considerable data concerning the squall lines of these dates. Much of these data had not been processed in time to be incorporated in this study. That portion which has been analyzed for this project is listed by aircraft type in the following sub-sections. Project aircraft carried beacon transponders to facilitate flight following on the ground radars.

MAY 4

DC-6 (USWB)

1. Position and navigation log from Doppler radar for time intervals of approximately 1 minute at flight altitude of 500 mb.
2. Ambient air temperature and drift angle for each position.
3. Time lapse moving picture of portion of squall line.
4. Portion of log from taped conversation between DC-6 and B-26.
5. Log of visual observations of squall line by flight meteorologist.

B-26 (USWB)

1. Log of tape recording by pilot of flight path and visual observations of squall line and flight conditions as flown at 850-mb. pressure level. This log also includes some observations of ambient air temperature and humidity.
2. Aircraft radar data logged in tape recording.
3. Debriefing notes of flight meteorologist on visual observations of cloud structure, turbulence, and moisture indications.

B-47 (Aeronautical Systems Division of USAF)
1. Flight log of track, position and time for operation at 30,000 to 31,000 ft. This contains a few entries on winds obtained from the Doppler radar, corrected air temperature, and remarks on radar storm echo range and distance.
2. Still photographs of squall line clouds at flight altitude.

U-2 (GRD)
1. Flight log of approximate track, heading, time, and geographical fix for a flight level of 66,000 ft. This log also includes remarks on turbulence and overall squall line cloud orientation.
2. Pilot's log summarizing cloud and turbulence observations.
3. Sample photographs of squall line development of May 17, 1961, in Oklahoma.

MAY 5

DC-6 USWB
1. Portion of log from taped conversation between DC-6 and B-26 in early part of flight during climb to 500-mb. pressure altitude.

B-57 USWB
1. Navigator's log of position, time, vortex temperature, altitude, and wind obtained from the Doppler radar. Flight level varied from 39,000 to 44,000 ft.
2. Time lapse moving picture film of squall line taken with wing camera.
3. Debriefing notes of flight navigator describing general flight pattern and extent of cloud buildups.
4. Notes, pictures, and log entries were also made for flight pattern circumnavigating a thunderstorm cell area near Ponca City.

B-47 (ASD)
1. Flight log of track, position, and time for operation at 28,000 to 33,000 ft. This log also contains a few entries on observed winds as measured by Doppler radar and corrected air temperature.

F-106 (ASD)
1. Debriefing questionnaire describing flight conditions and general cloud appearance prior to and during penetration of growing thunderstorm cell. Penetration was at a flight level of 40,000 ft. and at a supersonic airspeed.
2. Debriefing notes of pilot describing flight path, more detailed description of cloud structure and flight conditions encountered.

C-130 (GRD)
1. Debriefing notes of flight meteorologist describing mission along the squall line and near isolated thunderstorms. General cloud dimensions and characteristics are logged as flight was conducted at various flight levels from 25,000 ft. m.s.l. down to 1,500 ft. above ground.

C. TRAFFIC CONTROL DATA

The area covered by the St. Louis and Kansas City ARTCC is shown in figure 1. In all of the tape playbacks only one side of the two-way voice communication is recorded. Traffic information for the 4th of May is logged from the STL Center only, covering the two VHF channels reserved for civil and military high altitude traffic. Flight following for this position covers the southwest sector of the STL control area.

Tapes from STL for the 5th cover a few high altitude contacts and a larger number of acknowledgments in the low altitude position, again for the SW sector of the control area.

The logged tape data from the MKC Center covered two VHF channels used for flight following high altitude civil traffic on airways both north and south of MKC.

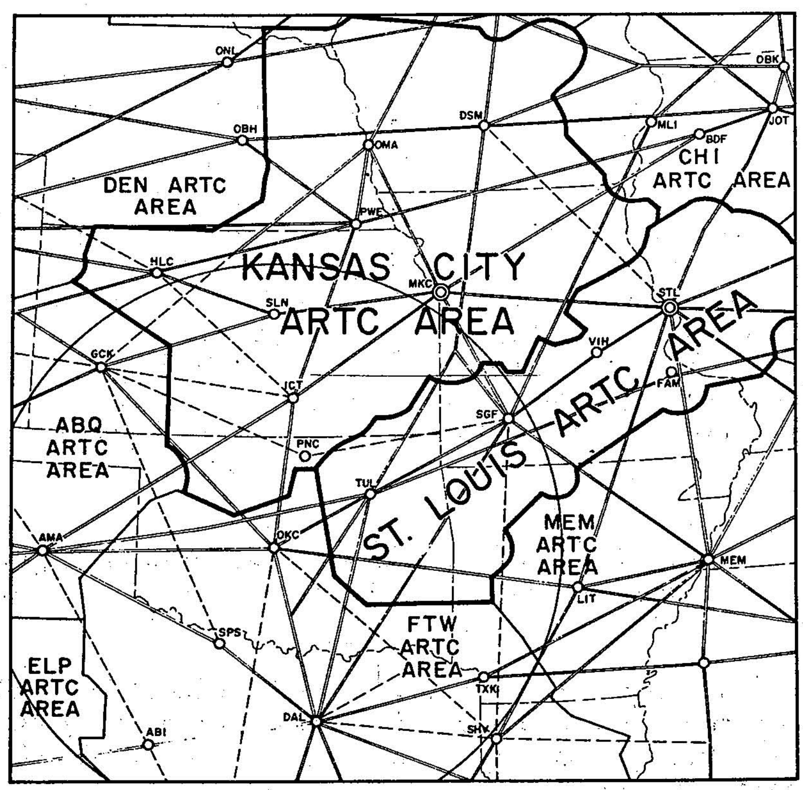

Figure 1.- Data as of June 1, 1962. Double lines are jet routes with Jet Advisory Service; broken lines are jet routes without Jet Advisory Service.

IV. MAY 4 CASE STUDY

A. SYNOPTIC SITUATION

The squall line and general thunderstorm activity which developed in Kansas, Oklahoma, and Texas was an occurrence not unusual for this section of the country in the spring. Figure 2 shows the general surface features at midmorning. This was not a new development but rather a carry-over from activity that was quite strong during the preceding night. A detailed analysis of certain features of this situation during the earlier night hours has been made by Williams [2]. A strong moist southerly current existed at 850 mb. and the winds at all levels up to 200 mb. were SW to W over Oklahoma at 1200 GMT. Maximum winds of 80 kt. were at 45,000 ft. and the tropopause was defined at 42,000 ft. at this time. A more complete description of the synoptic situation as related to the strong radar echoes which developed during the 4th, are presented in a paper by Hamilton [3].

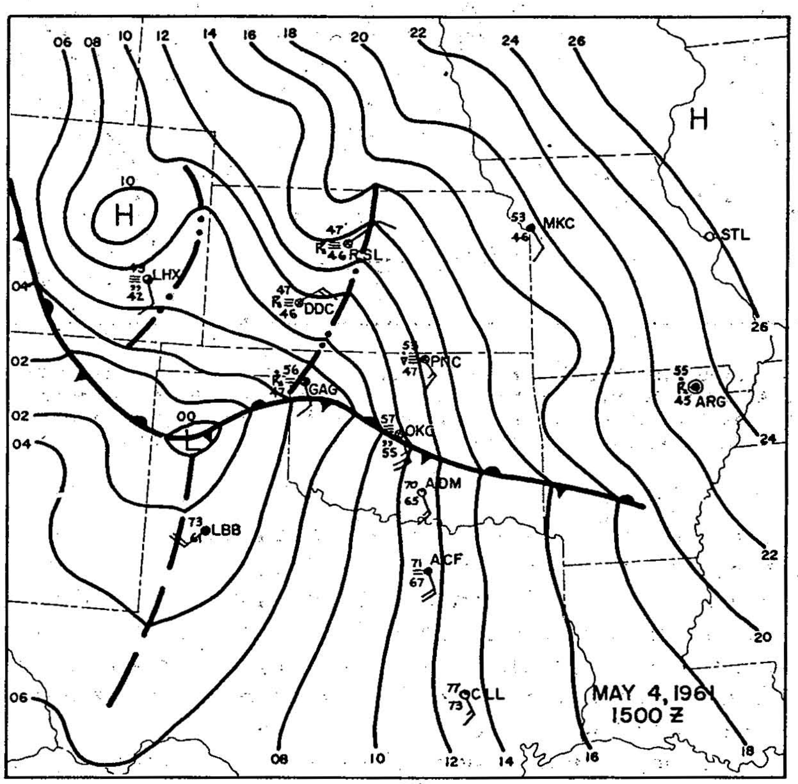

Figure 2.- Surface chart at 1500 GMT May 4, 1961. Isobars at 2-mb. intervals; fronts denoted by standard symbols; troughs associated with squall lines, heavy dash-dotted lines; long-dashed line is trough associated with western boundary of maritime tropical air.

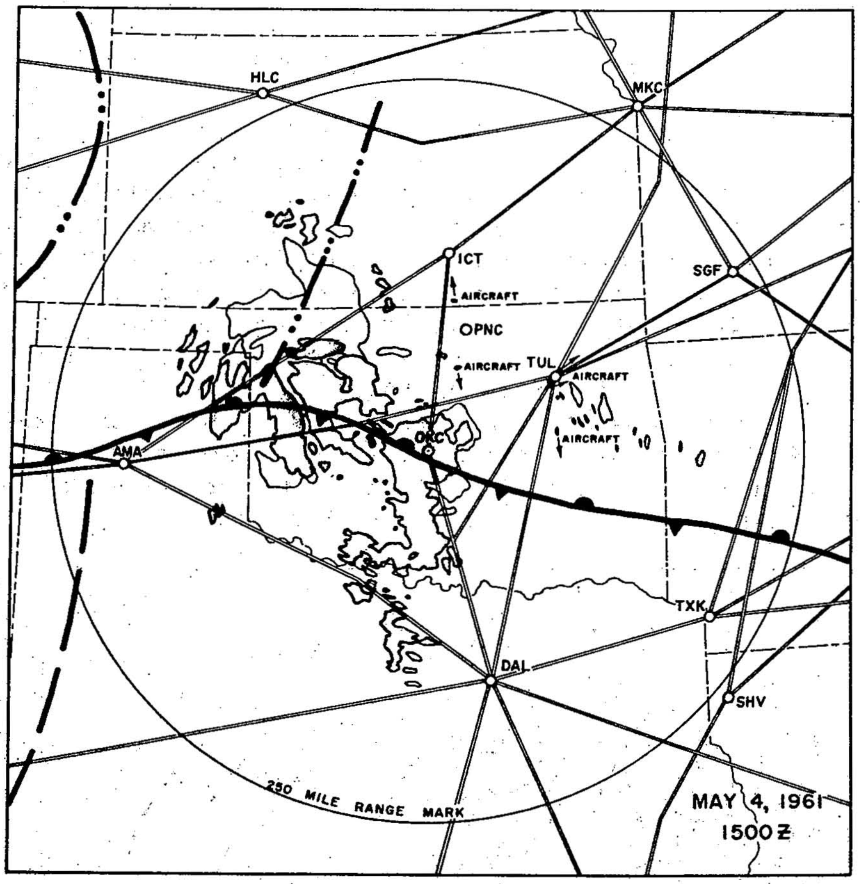

Figure 3.- The double lines in this figure and those that follow are the jet routes on which aircraft are provided Jet Advisory Service by the FAA. Additional jet routes on which this service is not provided have been omitted except where pertinent to the discussion of the traffic problem. All routes shown are those that existed in May 1961. See text for description of radar echoes.

B. DISCUSSION OF FIGURE 3

This figure is the radar echo pattern obtained from the OKC WSR-57 set (See Section III-A) at the same time (1500 GMT) as the surface analysis of figure 2. These echoes were obtained with 0° antenna setting and full receiver gain. Unshaded portions of the echoes correspond to the weaker, grainy returns of lighter precipitation. In the near vicinity of Oklahoma City in this and the following figures, the echo corresponds in part to "ground clutter" return not necessarily connected with storm echoes. Aircraft echoes that have been so identified by movement over a period of several minutes (successive frames) are shaded black and the current heading indicated.

It is apparent that the echo pattern at this time bears little resemblance to the frontal configuration, although new shower development is suggested on the warm front surface in eastern Oklahoma. The NNE-SSW oriented instability line in Kansas and Oklahoma at 1500 GMT has little radar support.

The Severe Weather Forecast (WW) Number 180 issued by the Kansas City SELS unit at 1240 GMT and valid for the time of figure 3 is as follows:

WW MKC FCST NR 180 041240Z

AREA 1 ... SVR TSTM FCST

A ... ALG AND 60 MIS EITHER SIDE OF A LN FROM 50 MIS WSW AMARILLO TEX TO 40 MIS NNW ENID OKLA. VALID 041300Z TIL 041900Z.

B ... A FEW SVR TSTMS WITH EXTRM TURBC 3/4 INCH HAIL SFC WND GUSTS SELY TO SWLY 50 K. ISLTD CB TOPS TO 50 THSD.

C ... SQLN CRNTLY 30 E HLC S AND SWD TO 20 E DHT EXPCD TO CONTU EWD 30 K NRN END SEWD 10 K WRN END.

AREA 2 ... SVR TSTM FCST

A ... ALG AND 60 MIS EITHER SIDE OF A LN FROM 30 NNW MIDLAND TEX TO 40 MIS N WICHITA FALLS TEX. VALID 041300Z TIL 1900Z.

B ... A FEW SVR TSTMS WITH EXTRM TURBC 3/4 INCH HAIL SFC WND GUSTS SWLY 60 K. ISLTD CB TOPS TO 55 THSD.

C ... TSTMS IN FCST AREA EXPCD TO INTNSFY WITH SFC HEATING ALG TROPICAL WRM FNT. PRIND THIS AREA MAY REQUIRE FCST OF MORE SVR NATURE BY ERLY AFTN. CHAPPELL

The Area 1 and Area 2 designated in this severe thunderstorm forecast encompass most of the activity showing on the radar at 1500 GMT. Only the scattered small echoes in eastern Oklahoma are outside the defined forecast zones.

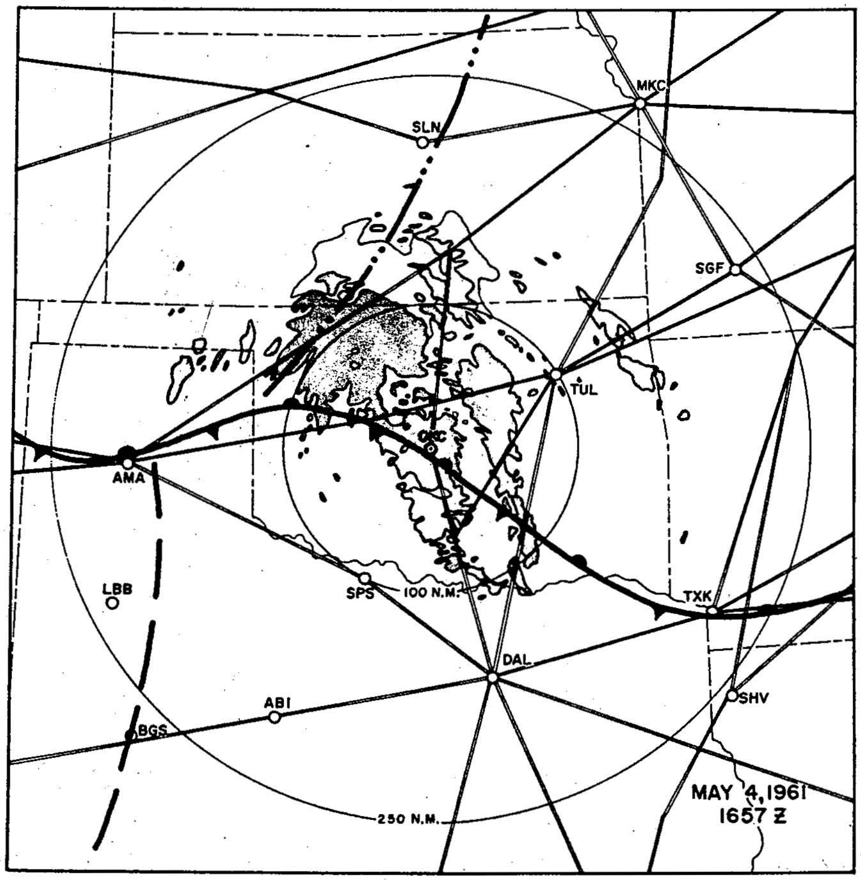

Figure 4

C. DISCUSSION OF FIGURE 4

Time: 1657 GMT

Radar range: 250 miles

Antenna: 0°

Gain setting: normal (0 db.)

In the 2 hours preceding this echo display, the cells have become more consolidated and the ill-defined lines of 1500 GMT have moved north and east. Warm sector activity has diminished and developments fit better the instability line and frontal configuration. There is a good suggestion of parallel bands spiraling in toward the surface low pressure center now positioned NE of AMA.

The DAL-AMA jet airway is now clear of cells, but airways north of DAL are crossed by thunderstorms. The Oklahoma City traffic NE and NW is faced with at least one line of development.

At 1615 GMT Severe Weather Forecast No. 181 was issued redefining and intensifying the development areas. The valid period began 1 hour following this pattern. (See discussion of fig. 6.)

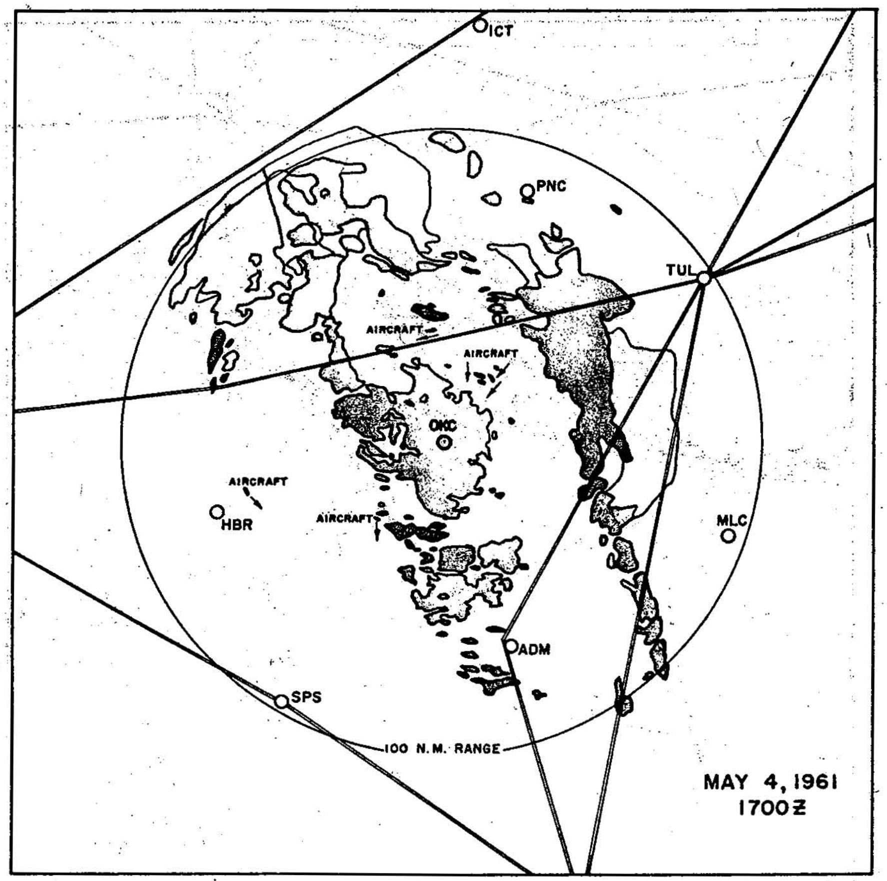

Figure 5.

D. DISCUSSION OF FIGURE 5

Time: 1700 GMT

Radar range: 100 miles

Antenna: 0°

Gain reduction: 18 db.

This figure is included to show in closer detail the cell developments portrayed in the previous figure (3 min. earlier). With 18 db. attenuation, these returns represent mostly moderate or heavy precipitation cores. Much of the echo within 10 or 15 mi. of OKC is ground clutter at this antenna setting. Aircraft depicted are probably at altitudes below 25,000 ft. with the exception of the flight WSW-bound on the jet airway out of TUL.

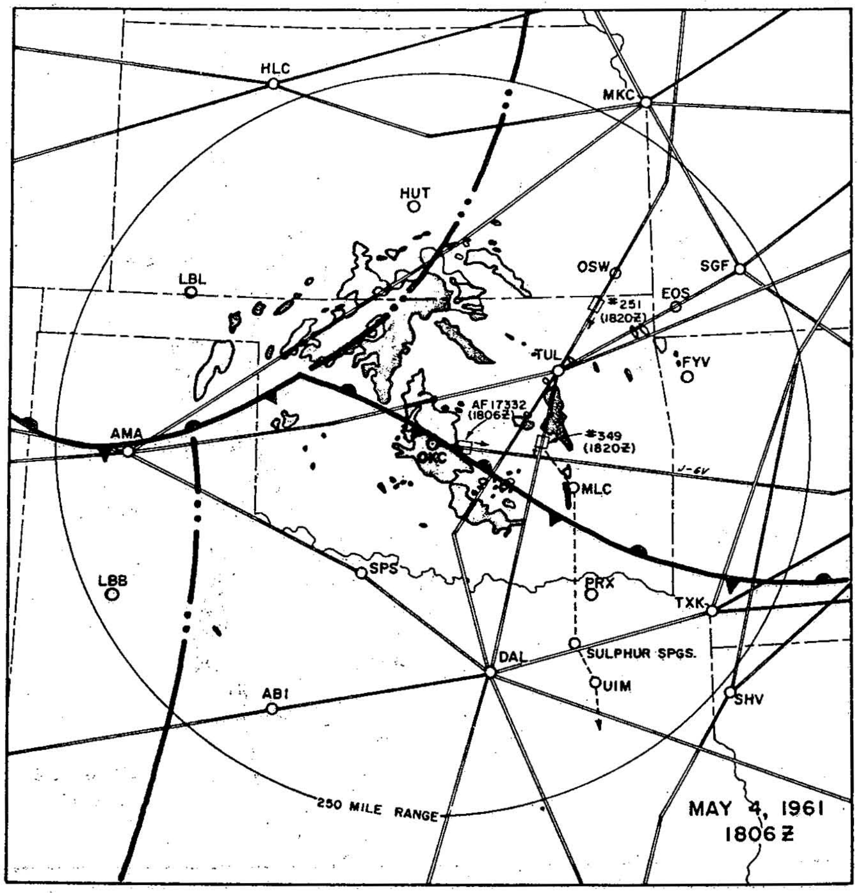

Figure 6.

E. DISCUSSION OF FIGURE 6

Time: 1806 GMT

Radar range: 250 miles

Antenna: 0°

Gain reduction: 24 db.

The solid cores of the important cells are portrayed here on this high gain reduction. Most lines of cells, when compared to the scope presentation in figure 5, have moved northeastward and new developments now appear on the warm front surface or the lower end of the Kansas-Oklahoma instability line. The dry "front" in west Texas is analyzed on its north end as a new line of development, not yet supported by radar evidence.

The first of the logged traffic control data from the STL Air Route Traffic Control Center follow, and are all acknowledgments of aircraft contacts by the Center. Time of acknowledgment is listed first.

1806 GMT: *AF 17332. Oklahoma City :04*, (flight level) *370, estimate Little Rock.*

1815 GMT (approx.): (Airline) *251. We slowed up for showers over Oswego* (OSW) - - - (DC-6 flight).

1820 GMT (approx.): (Airline) *251. Cleared to Tulsa omni at five thousand.*

1819 GMT (approx.): *SUNNY 02. Snow and light rime at nineteen thousand approaching Neosho* (EOS). (Aircraft type unknown and not plotted in figure).

1822 GMT (approx.): (Airline) *349. Requesting eleven thousand* (Pause) *Tops this area ten thousand to ten five. Now requesting fifteen thousand* (Convair 340 flight).

1828 GMT (approx.): relay from Fort Worth ARTCC: (Airline) *349. Unable clear to fifteen thousand but* (on) *rerouting requested, cleared to Houston, direct McAlester* (MLC), *direct Sulphur Springs, direct Quitman* (UIM). (Pause) *Estimating McAlester at Thirty.*

In the case of AF 17332, flight level 370 on jet route 6V was apparently clear of any serious weather problems since there were no further contacts from or to this aircraft. The other flights at low and intermediate levels were encountering weather not necessarily in agreement with the scope display here because of some time differentials and because the somewhat weaker cells would not show with this 24-db. gain attenuation. By 1820 GMT flight 349 had requested and been granted a change in flight plan rerouting as shown instead of by way of DAL, which route was being invaded by the SE end of the strong cells shown. (The echo near MLC had moved to the east of the rerouted track.)

The SELS Severe Weather Forecast No. 181 issued at 1615 GMT for a valid period 1800 to 0000 GMT called for some Tornado activity and the severe thunderstorms associated with the movement of the two instability lines. The complete forecast follows:

WW MKC FCST NR 181 041615Z

AREA 1 ... TORNADO FCST.

A ... ALG AND 60 EITHER SIDE OF LN FROM LUBBOCK TEXAS TO OKLAHOMA CITY OKLA DRG PRD 1800 TO 0000Z.

B ... TORNADOES HAIL ARND 2 IN DIA EXTRM TURBC SFC WIND GUSTS WLY 75 KT SCTD CBS WITH MAX TOPS 55 THSD.

C ... LN TSTMS EXPCD TO FORM ARND NOON VCNTY AMARILLO PLAINVIEW MIDLAND LN AND MV EWD AT ARND 30 KTS. PUB FCST ISSUED.

AREA 2 ... SVR TSTM FCST

A ... ALG AND 60 EITHER SIDE OF LN FROM LIBERAL KAN TO PARIS TEX DRG PRD 1800 TO 0000Z.

B ... HAIL ARND ONE AND HALF IN DIA EXTRM TURBC SFC WIND GUSTS WLY 65 KT NMRS CBS MAX TOPS 55 THSD.

C ... SERIES OF SHORT SQLNS EXPECTED TO MV E AND SEWD ACROSS W AND S OKLA. PUB FCST ISSUED.

AREA 3 ... SVR TSTM FCST

A ... ALG AND 60 EITHER SIDE OF LN FROM HUTCHINSON KAS TO FAYETTEVILLE ARK DRG PRD 1800 TO 0000 Z.

B ... A FEW SVR TSTMS WITH ISLTED HAIL 3/4 IN DIA AND EXTRM TURBC.

C ... OVRNG TSTMS EXPCD KAN MO NERN ARK EXPCD TO BE MOST INTS ABV AREA.

GEN TSTMS ... SCTD TSTMS OVER FLA EXPCD TO BE MOST NMRS AND INACTV EXTRM SRN PTN OF STA WITH GUSTY SFC WINDS SOME HAIL AND SVR TURBC. HOUSE.

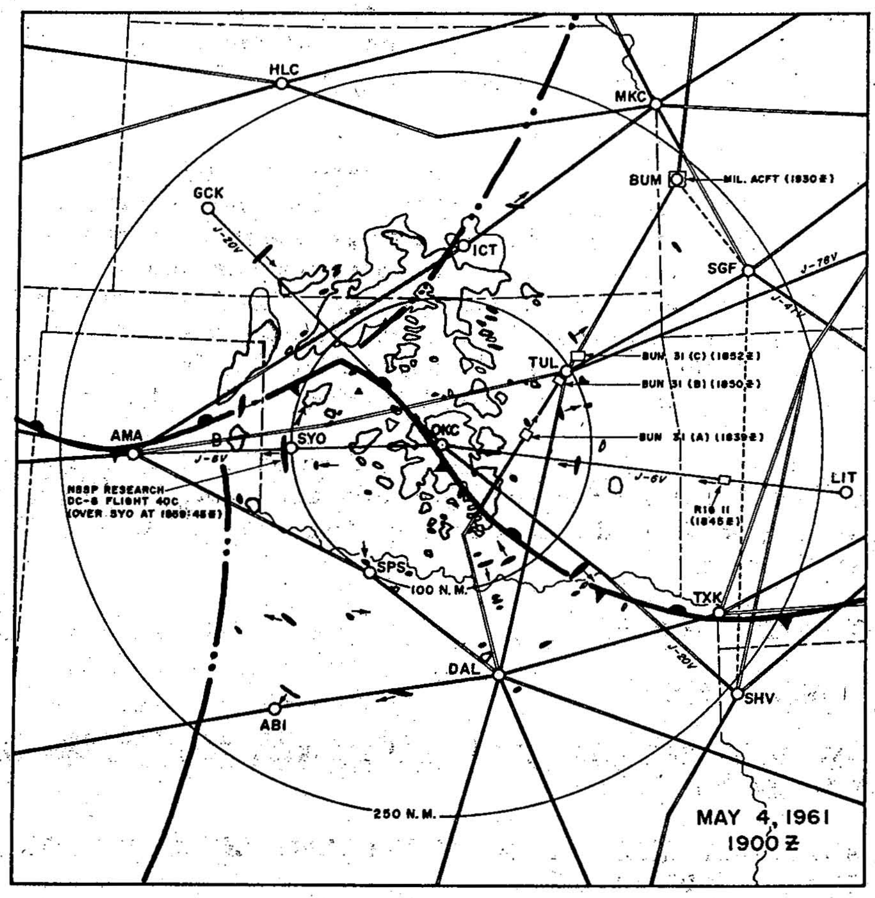

Figure 7.

F. DISCUSSION OF FIGURE 7

Time: 1900 GMT

Radar range: 250 miles

Antenna: 0°

Gain setting: normal (0 db)

Although there has been no significant change in frontal pattern between 1800 and 1900 GMT the ICT-AMA line development has become better consolidated and a new N-S line appears from ICT to southeast of OKC. The Texas instability line is now supported by radar with three or four cells. More aircraft echoes appeared on the scope at this gain setting. The NSSP DC-6 research aircraft outbound from OKC on the day's mission was identified by checking the Doppler radar position for this time. Plotted map position and the traced radar echo matched exactly. The Weather Bureau B-26 was also westbound from OKC to AMA (track not plotted) and pertinent observations are reviewed later in this section.

ST. LOUIS ARTCC CONTACTS

1839 GMT: *BUN 31. APPROACHING TULSA ON TOP AT* (flight level) *360, want higher altitude on return to Lake Charles.*

1850 GMT: *BUN 31. Eight miles south of Tulsa, inbound.*

1852 GMT: *BUN 31. In holding pattern at 310. Request change of destination to Tulsa.*

1845 GMT: *RIG 11. Little Rock* (LIT) *at thirty-three, on top at 400. Estimate Oklahoma City.*

1908 GMT: *HALE 43 requesting higher altitude. Given 390 over Vichy.*

1930 GMT: Discussion between HALE 43 and the STL Center concerning position of aircraft which had been planned MEM to TUL (via J-41V and J-78V). Thunderstorms made him plan to deviate north, "but not this far north".

The contact with the flight designated as BUN 31 implied that tops of the buildups SE and E of OKC were not above 36,000 ft. or at least were detourable at this altitude. A concern for anticipated vertical growth prompted the request for a higher flight level and finally the terminating of the mission at TUL could well have been directly related to the thunderstorm activity in this area.

Figure 7a.- This picture was taken from the SYO aircraft position shown in figure 7 looking NNE. The cumulonimbus in left center is the echo marked with the arrow. The smaller buildups at the left and right edges are too shallow to show on the OKC radar. The merged anvils on the horizon are from the squall line north of the frontal wave.

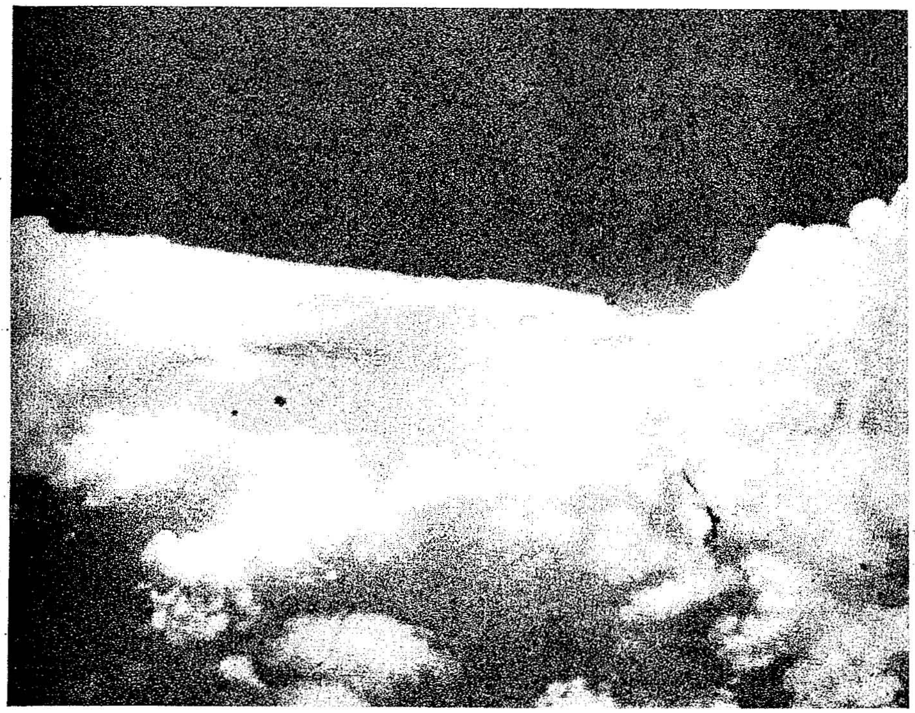

Figure 7b.- This view looking N from the DC-6 at 1908 GMT shows the break in the line of thunderstorms located just E of the dry line. The Cb on the left corresponds to the echo marked "B".

In the case of HALE 43, a deviation from plan to detour thunderstorms turned out to be a sizeable detour as thunderstorms continued to grow. Build-ups in the area concerned (NW Arkansas and SW Missouri) do not show in this scope picture because of distance but a broken moderate area with tops to 28,000 ft. was reported in the SD-1 Rarep Summary for this time. This is a good example of the inability to detect thunderstorm developments at distances beyond 200 mi. on ground radars, when cell growth has not reached 35,000 ft. or more. (Note the one small echo 50 mi. south of BUM.)

DC-6 RESEARCH FLIGHT LOG DATA

As indicated in figure 7 this NSSP flight was enroute from OKC to AMA on the route designated J-6V. The flight altitude was at the 500-mb. pressure level (just under 18,000 ft. m.s.l. on this leg). Ambient air temperature varied between -13° C. and -14° C., from SYO to AMA.

Comments by the flight meteorologist and single frame copies of 16 mm. cloud movies taken between SYO and AMA best describe the enroute conditions. See figures 7a and 7b.

1859 GMT: Weather in the area of SYO: Several large towering cumulus in the area. High scattered altocumulus above and scattered variable to broken stratocumulus below.

1904 GMT: Large Cb, top estimated at 35,000. Several other cells are also visible in this general area. (See fig. 7b for photo of this Cb, corresponding to the echo marked B.)

1908 GMT: Now approaching Shamrock. Several large cells observable. Large Cb in vicinity - top estimated 25,000. Several other large build-ups with tops up to about 22 or 23 thousand.

1918 GMT: We are now on the back side of the squall line. The squall line is oriented NNW-SSE.

1922 GMT: We are now in the clear air heading toward several other Cu buildups.

1931 GMT: Approaching AMA. Several small scattered Cu. Visibility 15 miles plus.

B-26 RESEARCH FLIGHT NOTES

This aircraft was assigned to fly a box pattern behind the squall line for dry air sampling. At the time of figure 7 the B-26 was between OKC and AMA, flying at 6,000 ft. m.s.l. The following are excerpts from debriefing notes which are pertinent to the analysis.

".... We were over Sayre at 1855Z. At 1859Z we skirted the side of a heavy cell off to our right about 10 to 12 miles, which would be north of us. It had a pretty good (radar echo) contour in it." (This would be Echo B).

"We passed through the dry line heading towards AMA at 1907Z,...50 miles east of AMA...."

From pilot's log: "The humidity has dropped from 8 grams to the east of this line to 2 grams on the west side...and there is a sharp break-off of the clouds."

The squall line specified in the 1918 GMT entry above is partially evident in figure 7, as the scattered line of echoes oriented NNW from the SW corner of Oklahoma. From the cloud photograph (fig. 7a) the wide breaks in the line are evident along with the growing cells. As will be noted from figure 8, this line became more solid 40 min. after the DC-6 passed through one of the large gaps.

Radar confirmation of the N portion of the squall line is also good from the B-26. The dry line noted by this flight also coincides with the surface analysis of the air mass discontinuity indicated.

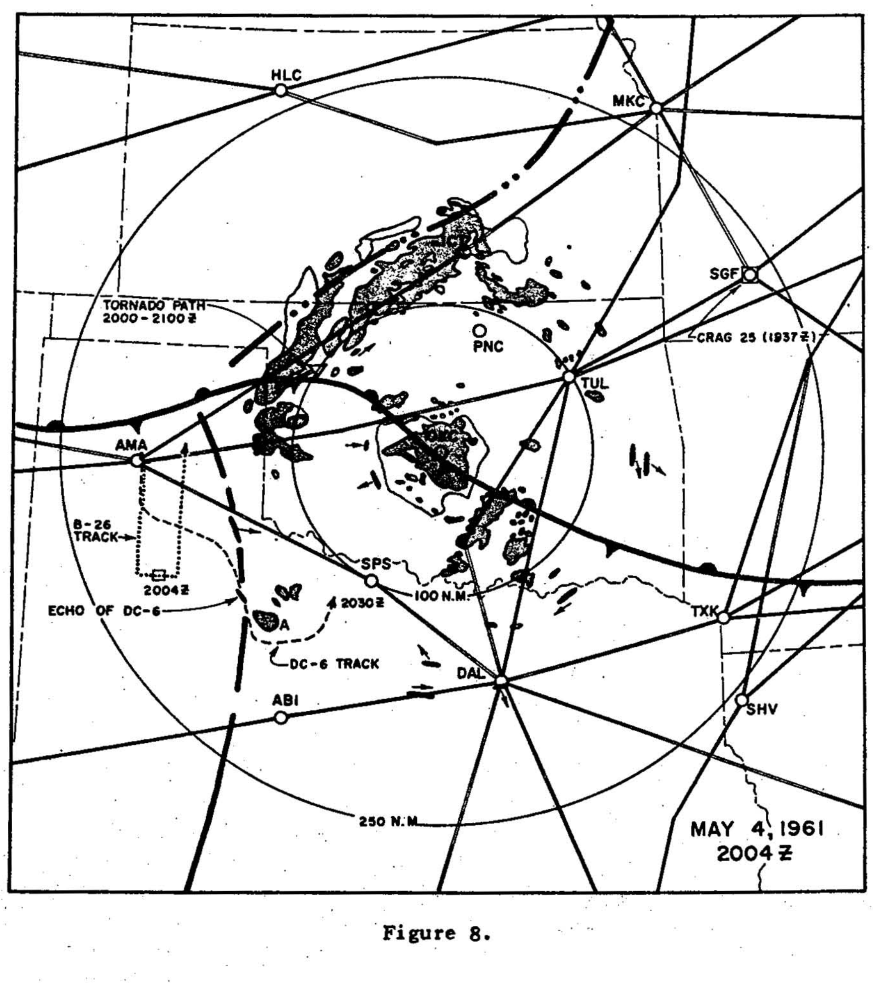

Figure 8.

G. DISCUSSION OF FIGURE 8

Time: 2004 GMT

Radar range: 250 miles

Antenna: 0°

Gain setting: normal (0 db.)

The massive NE-SW squall line which dominates more than 200 miles of the MKC-AMA jet airway is at this time the main feature of the radar echo pattern in this area. In the past hour, however, the OKC-PNC air traffic routes have cleared of thunderstorm activity, while an extensive outbreak has developed SE of the radar site within the 100 mile circle. The squall line penetrated by the DC-6 research plane W of SYO an hour earlier is less distinguishable as a line development, but the northernmost cells have intensified and are merging with the large squall line. Before the first of several tornadoes was reported (See 2000-2100 GMT tornado path) the WSR-57 radar controller logged the following:

"...strongest echoes look like about 286 (degrees), 120 miles...cells seem to be converging in this area."

Among the echoes identified as aircraft returns is one belonging to the DC-6 research flight - still at the 500-mb. pressure level. The track of this flight depicted here covers the period 1930 GMT to 2030 GMT. A box pattern was planned to be flown around the squall line. The NSSP B-26 research plane was also aloft at this time, flying at 850 mb. for dry air sampling in the box pattern shown. Because of the low altitude, the B-26 was not detectable by radar at this distance from the site.

ST. LOUIS ARTCC CONTACTS

1937 GMT: *CRAG 25. Over Springfield* (SGF) *280/290 requesting higher.* (Pause) Clearance given by STL ARTCC: *CRAG 25, cleared to 330/340.*

1945 GMT: *SNUG 1 approved 390 from 370.*

1954 GMT: *SNUG 7. Diverted to Springfield, flight level 380 on top.*

Destinations and missions of these three military flights were not indicated in the ARTC tapes, but it is probable that the changes in clearances indicated in the logs were weather-influenced. The SGF area fell within a zone defined by the 2100 GMT SD-1 Rarep Summary as "broken, moderate echoes with average tops to 30,000". Again the OKC radar was unable to pick up these developments because of distance, the effects of earth curvature, and the variable refraction of the radar beam in a changing atmosphere.

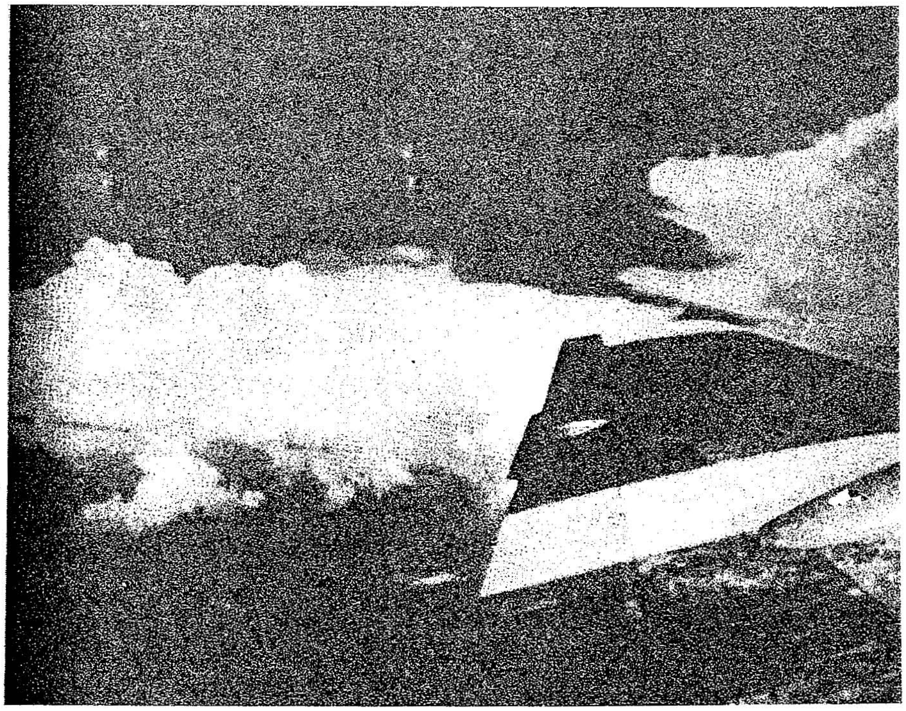

Figure 8a.- This photograph is taken looking east from the 2007 GMT position of the DC-6. The anvil on the right is from the cell marked "A" in figure 8. The rest of the buildups are part of the northeastward extension of this area of activity.

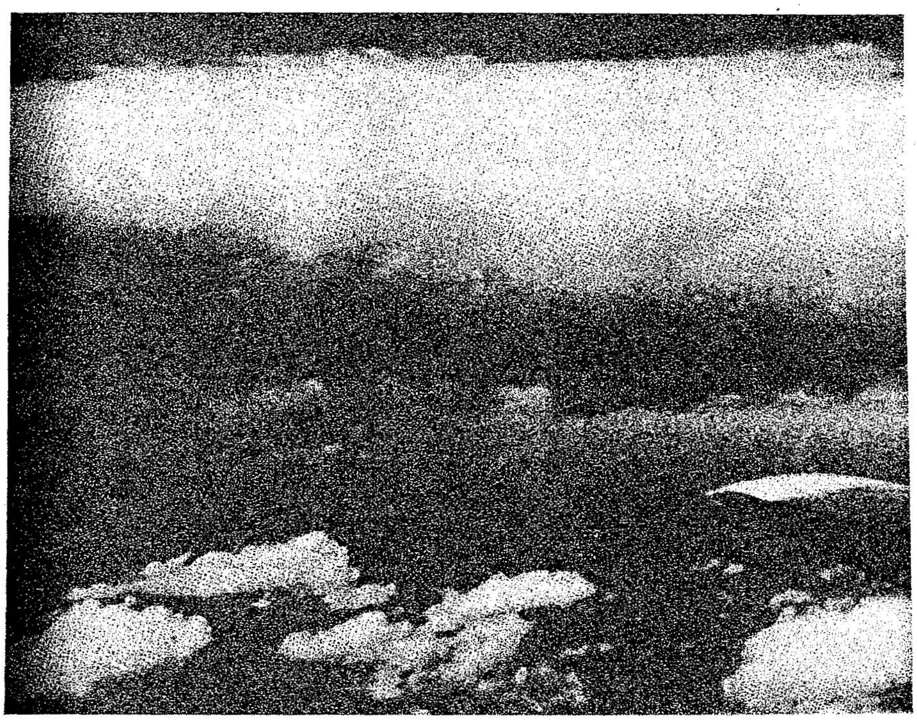

Figure 8b.- At the 2021 GMT position of the DC-6 this picture was taken toward the N underneath an anvil cloud which developed either off Echo A or from a new cell in this cluster of echoes. Mammatus formation is clearly evident on the bottom. Clear skies at the upper edge of the picture mark the top of this anvil.

DC-6 RESEARCH FLIGHT LOG DATA

2000 GMT: Buildups reported from radar contact 40 n. mi. from our position 155° magnetic heading. (This corresponds well with the position in fig. 8 of the echo labelled "A" bearing SE from the DC-6 aircraft position.)

2002 GMT: Scattered Cu to the right of our aircraft along our heading. Towering Cu to the left of our aircraft with tops estimated between 18,000 and 25,000.

2006 GMT: Towering Cu buildups increasing. Tops generally ranging between 18,000 and 19,000 ft. We are 12 n. mi. from radar echo. Cb cloud with top estimated at about 35,000 plus - location just E of our aircraft. (This buildup is Echo "A" in fig. 8, part of which is photographed in fig. 8a.)

B-26 RESEARCH FLIGHT DATA

From debriefing notes: ".... We were over AMA at 1928Z...in the dry air registering one gram of moisture per cubic meter. We were flying south...over Plainview we noticed a line of dust devils oriented NNE-SSW. A couple of them looked like they were as high as 200 feet.... This was approximately 1958Z."

From pilot's log: "... We turned on the SE corner of our box. Doppler is now programmed for 350 degrees, 130 miles. .... We now have 98 miles to go on this leg. A line of thunderstorms showing on the weather radar from about 30 degrees off our nose at 110 miles approximately."

The aircraft radar from this lower altitude and at the S end of the northbound leg was picking up only the strongest (and highest) cells of the NE-SW squall line. The activity nearer the aircraft was apparently not recognized as part of the line from this distance.

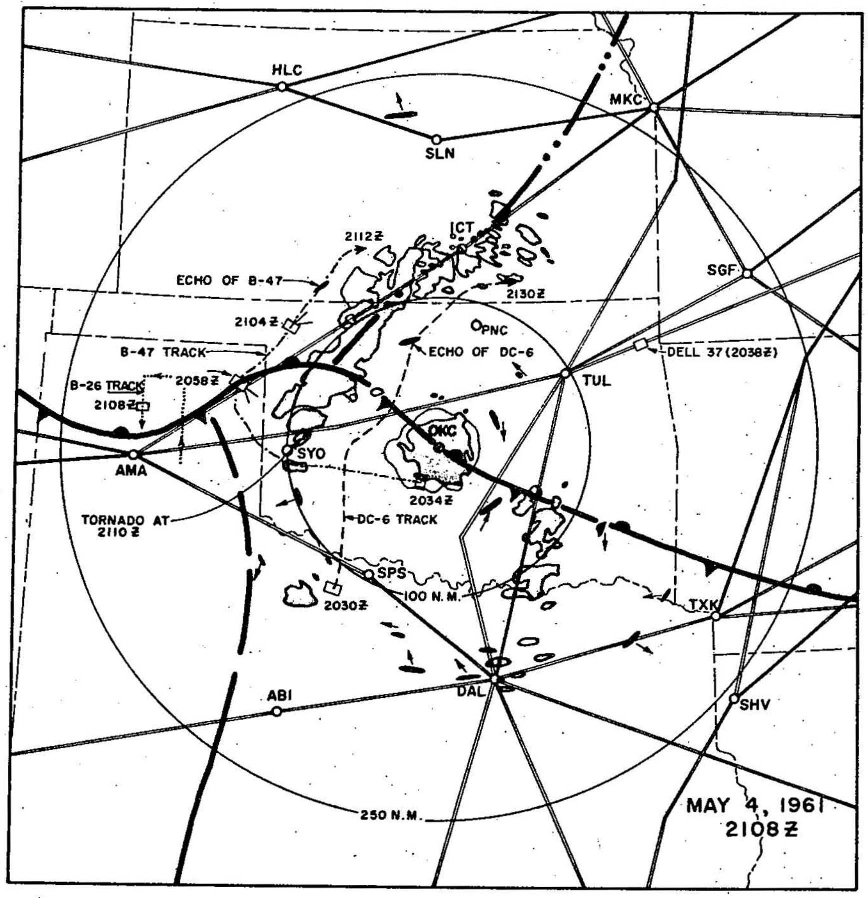

Figure 9.

H. DISCUSSION OF FIGURE 9

Time: 2108 GMT

Radar range: 250 miles

Antenna: 0°

Gain reduction: 6 db.

During the past hour the lower portion of the NE-SW squall line has moved eastward but the upper end continues to block the MKC-AMA jet airway. The group of cells near Sayre (SYO) have consolidated and just about merged with the lower end of the main line of thunderstorms. New cells on the lower end produced a tornado, reported at this time as indicated.

In the area SE of OKC and N of DAL a new N-S line appears to be shaping up. The DC-6 and B-26 research aircraft continued in their two flight patterns as plotted. The DC-6 was foiled in completing a box around the squall line by the intensity of the development and was forced NE and E toward SGF. A third member of the aircraft fleet, a B-47, was added at this time on a photographic support mission. The path flown by this unit at 30,000 ft. is traced in figure 9 from plots of the radar echo position as observed from the WSR-57 at 2-min. intervals.

ST. LOUIS ARTCC CONTACT

2038 GMT (Contact directly from Flight): *DELL 37 fifty miles E of Tulsa diverting to Lake Charles. Over Tulsa 2030Z. Originally planned McConnell, Lackland, McConnell* (Wichita - San Antonio - Wichita).

The diversion of this B-47 mission was probably connected with the current squall line activity near ICT and its anticipated movement to the east which would have necessitated a high altitude penetration of the thunderstorms.

DC-6 RESEARCH FLIGHT LOG DATA

2104 GMT: Extensive Cb west of our aircraft. Extensive lower cloud deck and a layer of cirrus above.

2115 GMT: Large towering Cu northeast of our position. Lower solid undercast of building Cu whose tops are about 17,000. Some scattered to broken clouds above.

2127 GMT: Several towering Cu in our area.

All three of these observations describe the general flight conditions at 17,000 ft. while paralleling the extensive line squall. Note that the flight was conducted very near to some of the shower echoes toward the NE end of the line but apparently well below the blowoff layers at this flight level.

B-26 RESEARCH FLIGHT NOTES

Remarks from this portion of the box flight pattern flown at 5,000 ft. were centered around the change in moisture across the stationary front and the line of lower fracto-cumulus which defined the front's position. All observations confirmed the low level analysis as shown, with moisture increasing (northbound) from 1 gram on the warm, dry side to 6 grams in the cold moist air.

B-47 RESEARCH FLIGHT NOTES

Two photographs have been selected from this flight to depict the general cloud structure of this squall line while the flight was traversing the west side of the activity: Figure 9a, taken from the 2058 GMT position, and figure 9b from the 2104 GMT position.

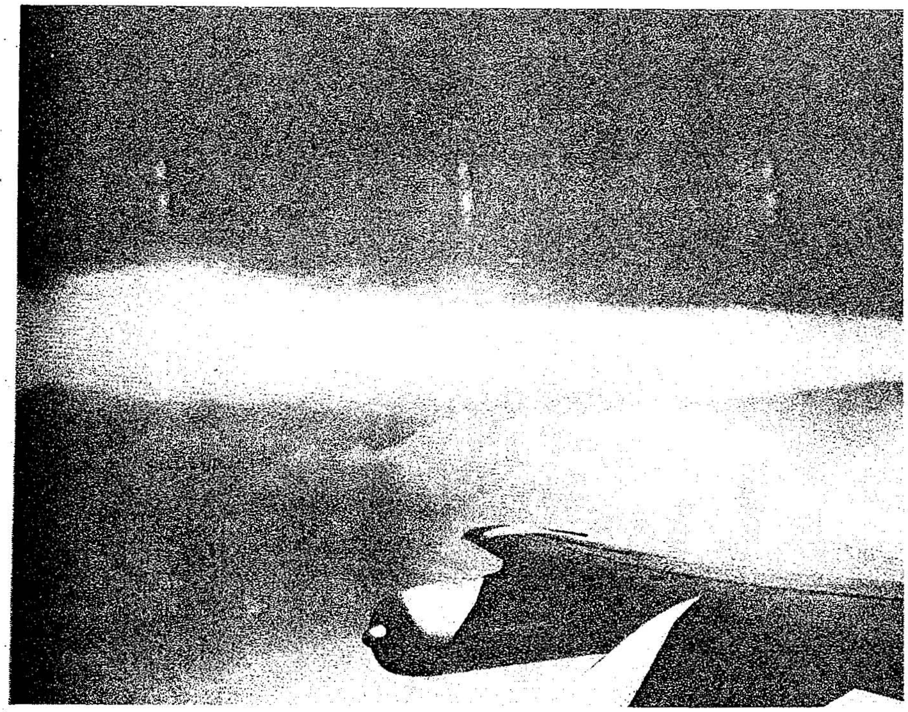

Figure 9a.- This picture is aimed in a direction of 160° or toward the south end of the big line. Note that the bottom of the anvil is above the flight level of 30,000 ft. The tornado which occurred at 2110 GMT is on the far side of the heavy development near the left edge of the photograph.

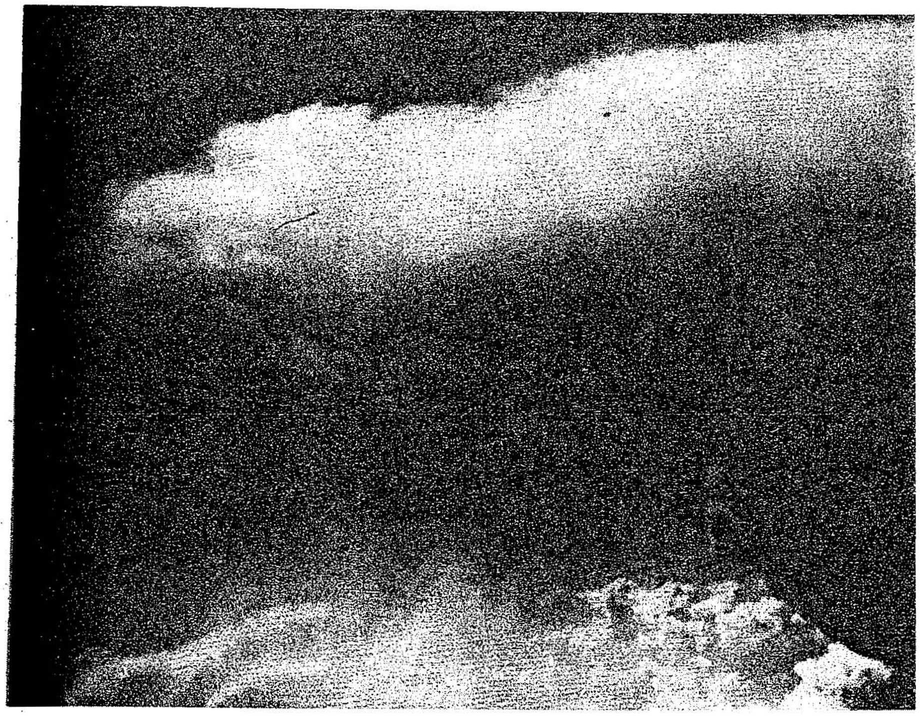

Figure 9b.- This photo was taken at 2104 GMT looking NE along the NW edge of the center section of the squall line. The anvil shown corresponds to the unshaded portion of the figure 9 echo NE of the aircraft. There is apparently considerable water in this shelf of cloud - enough to produce a return with 6-db. attenuation. Winds near this point were measured with the B-47 Doppler radar as 215 degrees, 60 kt., or in a direction away from and to the left of the camera angle. Ambient air temperature was logged as -34° C.

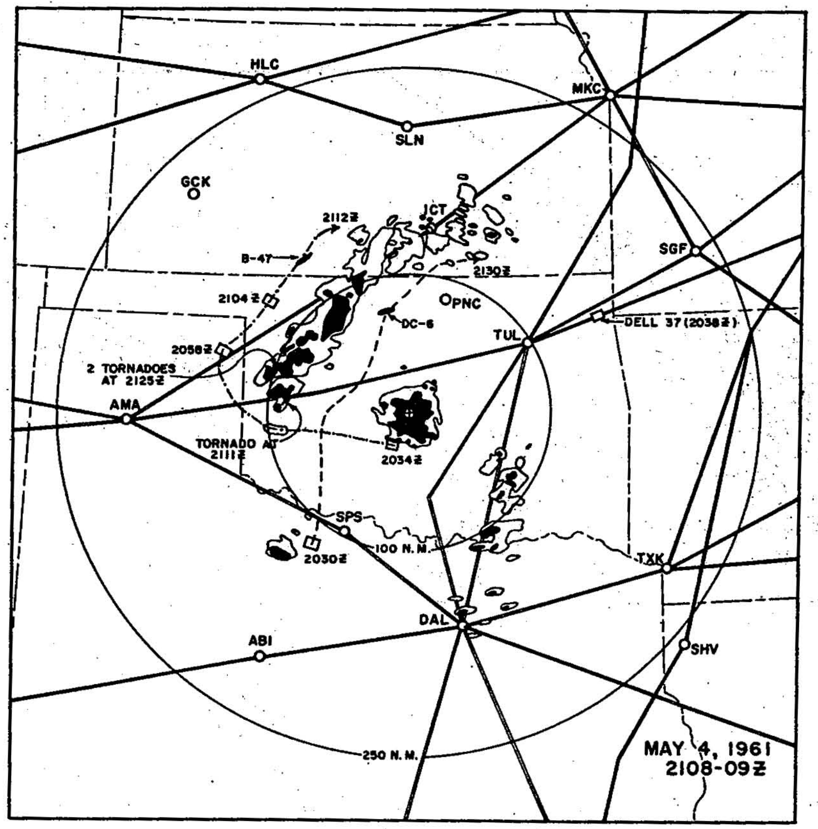

Figure 10.

I. DISCUSSION OF FIGURE 10

Time: 2108 and 2109 GMT

Radar Range: 250 miles

Antenna: 0°

Gain reductions: 6 db. and 24 db.

This is a composite of the scope display of figure 9 and of the corresponding picture obtained 1 min. later with 24 db. of attenuation added to the receiver gain. Only the hard cores (dark shading) of the strongest developments remain at this high step gain reduction. It is obvious that except for one or two cells the northeast half of the large squall line is in a decaying state. The newer N-S line north of DAL and the cell SW of SPS are both potent (and growing) areas.

At least three tornadoes were occurring at or near the time of this composite scope picture. Locations are indicated and it is to be noted that no "figure 6" or hook-shaped configuration to the echoes can be recognized at this distance.

All aircraft scope returns have been deleted from figure 10, except for the echoes belonging to the DC-6 and B-47 research aircraft.

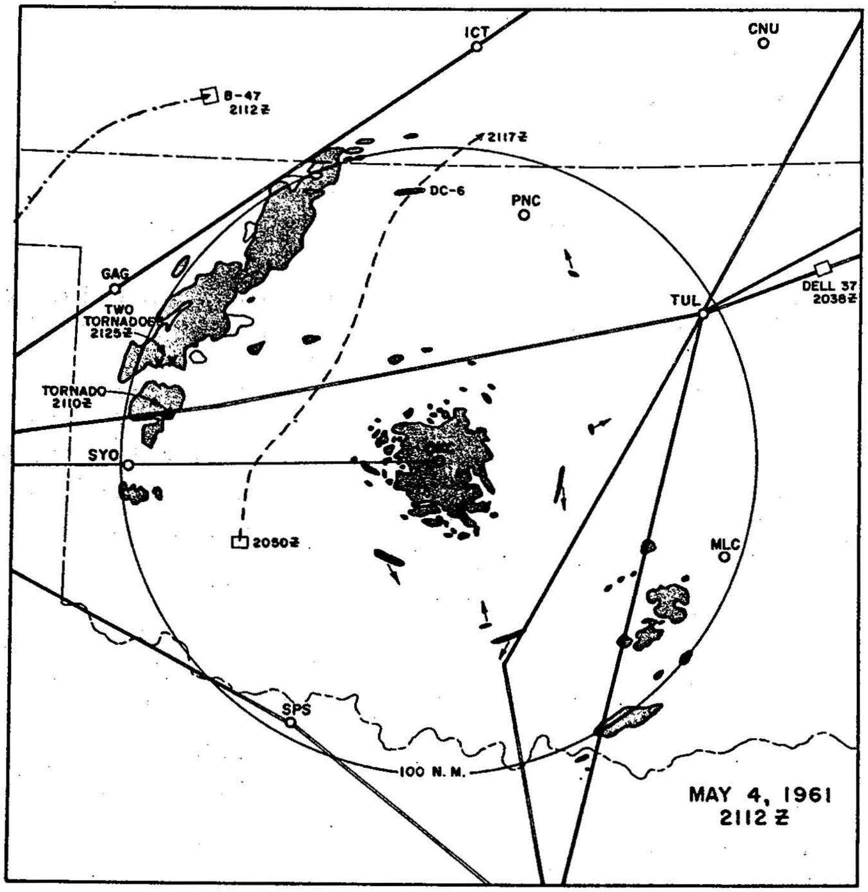
ICT
CNU
B-47
2112Z
2117Z
DC-6
PNC
GAG
TWO
TORNADOES
2125Z
TUL
DELL 37
2038Z
TORNADO
2110Z
SYO
2050Z
MLC
SPS
100 N. M.
MAY 4, 1961
2112 Z

Figure 11.

J. DISCUSSION OF FIGURE 11

Time: 2112 GMT

Radar range: 100 miles

Antenna: 0°

Gain reduction: 12 db.

The line of strong echoes has moved in closer to OKC and the details of the tornado-producing squall line are shown in the 100-mi. range.

Note that the tornadoes are being generated in the peripheral areas of the strong echoes. A comparison of this scope display with figures 9 and 10 shows up the differences between detailed presentation and the coarser broad-scale patterns. This same detail is, of course, also displayed on the standard aircraft radar scopes when set on intermediate range.

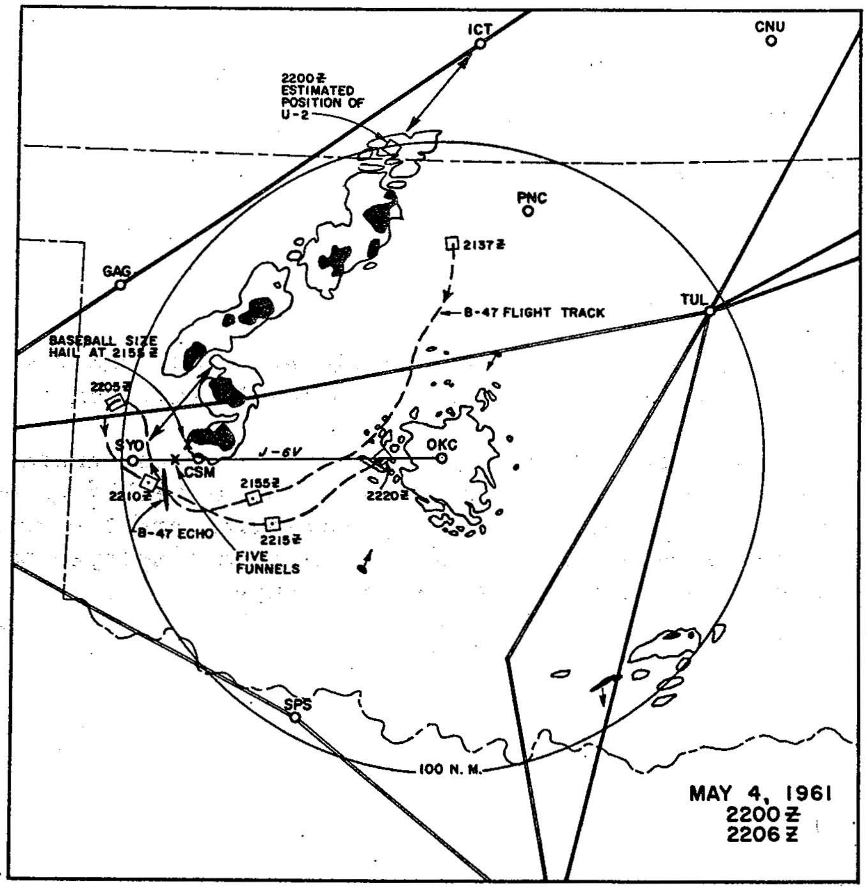

Figure 12.

K. DISCUSSION OF FIGURE 12

Times: 2200 and 2206 GMT

Radar range: 100 miles

Antenna: 0°

Gain: 0 db. and 36 db. gain reduction

This is another composite made from two scope pictures 6 min. apart. The hard cores (black shading) are from very heavy precipitation which is giving a return even with nearly full attenuation (36 db.) switched into the system.

Movement of the integrated segments of the squall line since 2112 GMT has been SE with no apparent northward drift of individual cells.

The baseball size hail reported on the ground at 2155 GMT was, like the tornadoes earlier, a peripheral development on the rear of a well developed cell. The five funnels reported "west of CSM" were sighted from the B-47 research flight from the 2215 GMT position. The track of this flight as shown in figure 12 is the plot of successive 2-min. positions of the radar echo from the B-47.

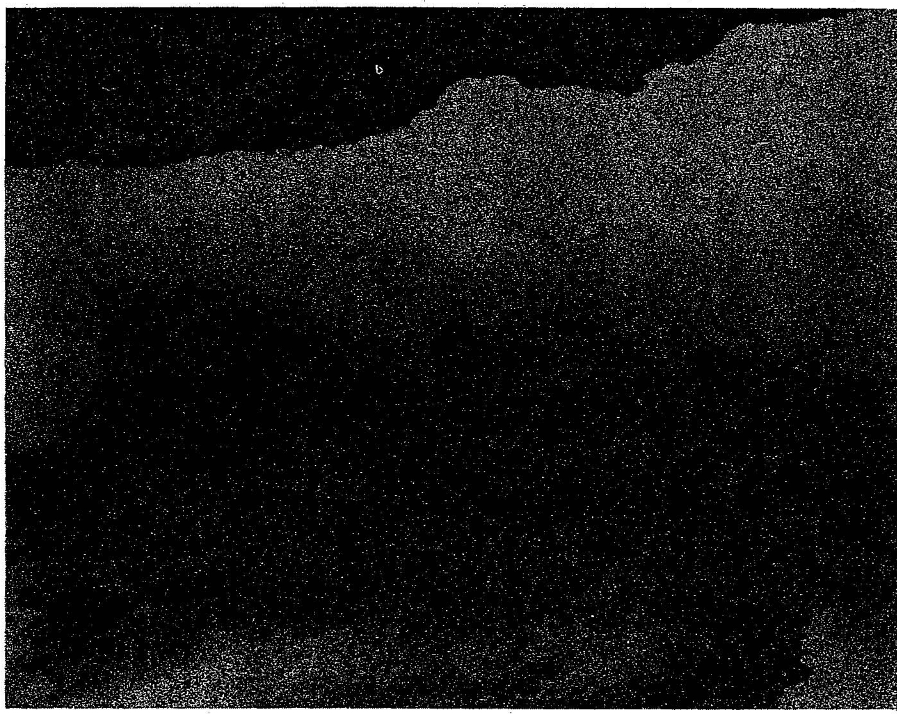

Figure 12a.- Looking directly into the intense south end of the squall line from a distance of about 12 mi. to the nearest echo. Tornadoes and large hail were occurring at this time below the dark shadow area on the left. Note the density of the cloud layer above flight level with indications of strong vertical growth still taking place.

A U-2 aircraft assigned on this day to NSSP was making observations from 67,000 ft. At scope picture time this flight was approximately at the position indicated flying on a track from ICT to SYO. This path nearly coincides with the axis of the squall line.

B-47 FLIGHT LOG EXCERPTS

2155 GMT: Altitude, 31,000 ft.; heading, 245; bearing of photo from B-47 - 3:00 o'clock. (This photo is fig. 12a.)

2205 GMT: Cloud tops at south end of line estimated to be 42,000 to 50,000.

U-2 Pilot Log Excerpts

"...reported the frequent occurrence of swelling cumulus (sic) tops bursting rapidly through thin cirrus anvils and extending upward above the general cirrus level for several thousand feet. Of great interest is the pilot's observations of periodic up-and-down-drafts along the flight path between Sayre (SYO) and Wichita (ICT), from his estimate of their frequency, the wavelength would appear to have been between 10 and 20 miles...."

At 2116 GMT, a new Severe Weather Forecast (No. 182) was issued by the SELS unit of the Weather Bureau calling for tornadoes, hail, and severe thunderstorms in areas showing some signs of development SW and SE of OKC on the 2108 GMT radar display (fig. 10). The forecast was valid from 2200 to 0400 GMT.

WW MKC FCST NR 182 042116Z

AREA 1 ... TORNADO FCST

A ... ALG AND 60 EITHER SIDE OF LN FROM ABILENE TEX TO 60 NW OF TEXARKANA ARK DRG PRD 2200 TO 0400Z.

B ... TORNADOES HAIL ARND 2 IN DIA EXTRM TURBC SFC WIND GUSTS WLY 75 KT SCTD CBS MAX TOPS 55 THSD.

C ... AT 2100Z LN TSTMS VCNTY HOBART OKLA ABILENE TEX LN MVG EWD AT ARND 30 KTS EXPCD TO CONTU EWD MVMNT NEXT 6 HRS. PUB FCST ISSUED.

GEN INFO ... CONTU FCST NR 181 UNTIL EXPIRATION TIME OR UNTIL PASSAGE OF LN TSTMS REFERRED TO IN C ABOVE. HOUSE.

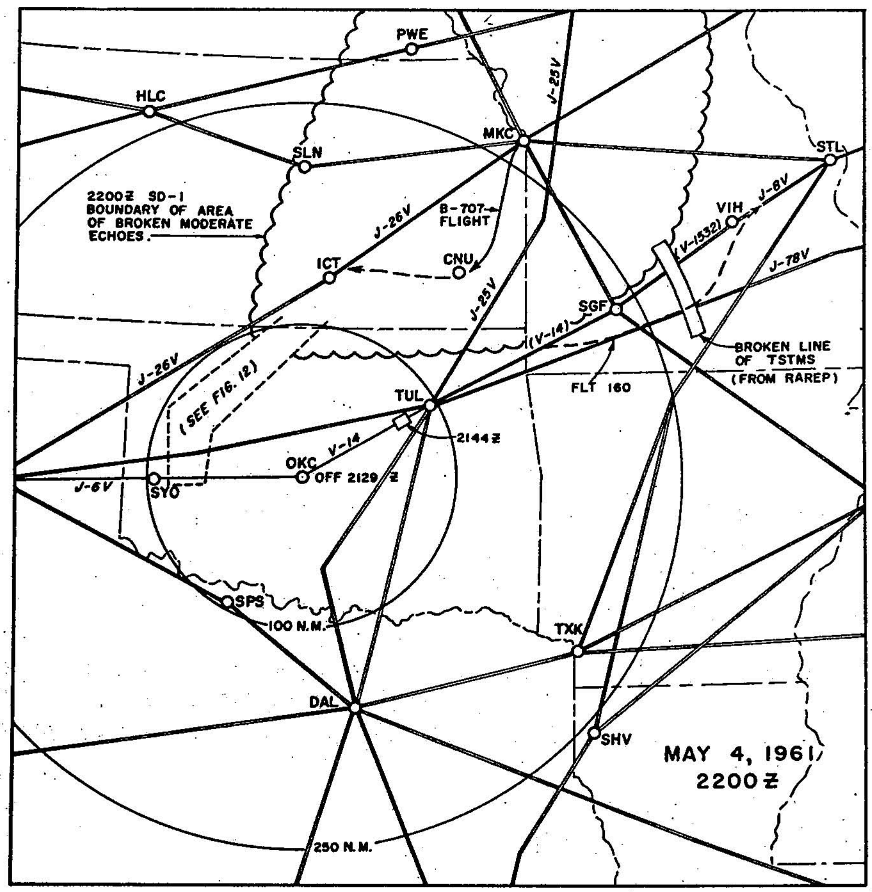

Figure 13.

L. DISCUSSION OF FIGURE 13

Time: 2200 GMT

No echoes are reproduced in this figure which is off-centered from OKC to depict two flight plan detours in southeastern Kansas and southern Missouri. The thunderstorm pattern which affected these flights was not available from the WSR-57 radar between 2112 and 2225 GMT. During this period the 100-mi. range was required for Weather Bureau tornado warning purposes. The Rarep Summary (SD-1) for 2200 GMT is used in part to define the thunderstorm radar pattern correlated to the air traffic problem for this hour.

ST. LOUIS ARTCC CONTACTS

2144 GMT: (Airline) *160 requesting OKC-TUL-VIH at 250. Off OKC 2129Z.*

2146 GMT: (Airline) *160, approved routing via Victor 14, Victor 1532, Jet 8.*

2148 GMT: (Airline) *160, requesting detour 10 south of course short of VIH.* (Pause) *Will you be back on course by VIH* (Pause) *No, want to use J-78 by SGF.*

2205 GMT: (Airline) *160 Springfield :58, estimating Vichy :08. Detoured south of course.*

2212 GMT: *Boeing 707 deviated south of course on 190 degree heading, 30 miles west of J-25 Victor and turning toward Chanute* (CNU) *to get back on J-26 Victor. Flight level 310.*

2218 GMT: (Voice communication on STL Center frequency probably from MKC ARTCC). *Advise aircraft of severe weather cells between Sayre and Oklahoma City moving east. Tops to 50 thousand or higher. Tornado reported in cell. Can possibly get around by deviating south.*

The detour planned by Flight 160 (Convair 880) after passing TUL was apparently based on knowledge that the line of thunderstorms up ahead could be penetrated safely through breaks toward the south end of the line.

The Boeing 707 detouring out of MKC was avoiding thunderstorms in an area described by the 2200 GMT Rarep Summary as "broken moderate with tops 30,000 ft."

The south end of the severe squall line which was generating some of the tornadoes (See figs. 12 and 14) was recognized by MKC ARTCC as a trouble spot for the control of aircraft along route J-6V and the advisory was passed on to the STL Center.

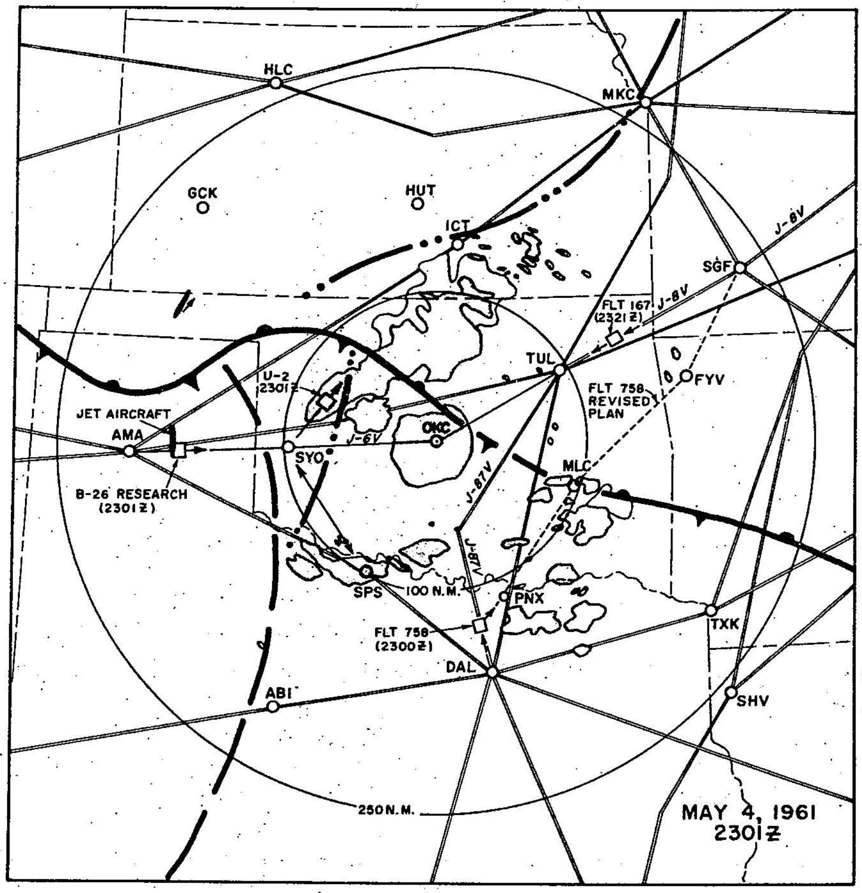

Figure 14.

M. DISCUSSION OF FIGURE 14.

Time: 2301 GMT

Radar range: 250 miles

Antenna: 0°

Gain setting: 0 db.

The northern portion of the NE-SW squall line has shown further signs of decay in the past 2 hours as cells become smaller and detached, or grainy (unshaded area). The south end, however, is still very potent, the radar room log commenting on the strong cores and RHI indicating tops to 50,000 or 60,000 ft.

In terms of the radar analysis the Kansas instability line should have been located east and south of ICT to coincide with the squall line axis. The position shown has been analyzed without the help of surface data which were missing in the area.

The new NNE-SSW instability line in western Oklahoma has no radar support at this time and only weak substantiation 2 hours before.

The most significant change on this map is the increased activity in the warm sector from west of SPS to the MLC-PNX area. Two research flights were collecting data for this period. The U-2 had just completed a round trip at 67,000 ft. between SYO and SPS and at 2301 GMT was starting the second time out on the SYO-ICT leg. The only pertinent data in the pilot's log for this time period was a note of "a large Cb a little south of SPS" at 2235 GMT and entries of light turbulence from 2255 to 2315 GMT.

The B-26 was eastbound from AMA at 5,000 ft. to fly a box pattern near SYO, closer to the squall line. Estimated position of the aircraft is indicated in the figure. Pertinent observational details follow:

B-26 RESEARCH FLIGHT NOTES

".... We have echoes sbout 50 degrees at 100 mile range; also have echoes about 30 degrees off to the right of our nose at about 100 to 125 miles...."

These aircraft radar observations correlate closely with the WSR-57 echo pattern as shown and confirm the fact that a wide gap exists on the J-6V airway in the line activity that is presented in the surface analysis and in the SD-1 radar summaries.

ST. LOUIS ARTCC CONTACTS

2230 GMT: *AF 16724, Tulsa estimate 2244Z.*

2231 GMT: (FTW ARTCC asking STL ARTCC): *Will he be able to get radar vectoring around the weather?* (Answer): *Don't know. No radar here. Can stay VFR by detouring 20 miles south of J-6V.*

2250 GMT: (Airline) 758: *Dallas J-87V to Tulsa, J8V to St. Louis at 250* (Electra).

2252 GMT: (Discussion between STL and MKC Centers on how best to flight follow this Electra with the Hutchinson radar inoperative. Decision was made that MKC ARTCC would flight follow with their radar.)

2302 GMT: (Airline) 758. *35* (miles) *north of DAL. PNX, direct MLC, direct FYV, SGF, J-8V to STL. Now request this plan. Estimate over MLC 2323Z at 250.*

2321 GMT: Airline *167, requesting high altitude to low after TUL.* (Pause) *O.K. take him down to 10 thousand from 290 after TUL at approximately 2345Z, via J-8, V-1532, V-14 to OKC* (See also fig. 15).

The military aircraft, apparently westbound over TUL to OKC and points west, was aware of the activity near OKC and close to but north of J-6V airway. The STL Center, from radar information relayed by MKC and from flights traversing the sector, was able to give a good steer to this aircraft which kept him clear of the severe thunderstorm area.

In the case of the Electra flight 758, the original plan filed by way of J-87V would have been the preferred route from a weather standpoint. The request for change in plan as shown via FYV may have been prompted by (1) shorter distance and fuel or time considerations (new route 4 minutes shorter), (2) poor forecasting of the thunderstorm development on J-87V, or (3) lack of complete or correct data on current thunderstorm activity. In any case, as will be seen not only from figure 14, but also from figure 15, J-87V remained clear of thunderstorms until well after the MLC estimate, while "needle-threading" with his own radar must have been required between PNX and MLC.

The request from Flight 167 for a quick descent to a low altitude after TUL implies a concern for the increasing shower activity in the OKC area (hidden in ground clutter in fig. 14, but evident in fig. 15) and the threat from the squall line NW of this airport. A descent clearance into the approach pattern from 10,000 ft. would involve less risk of moderate turbulence than a longer descent through or near the increasing activity in the approach zone.

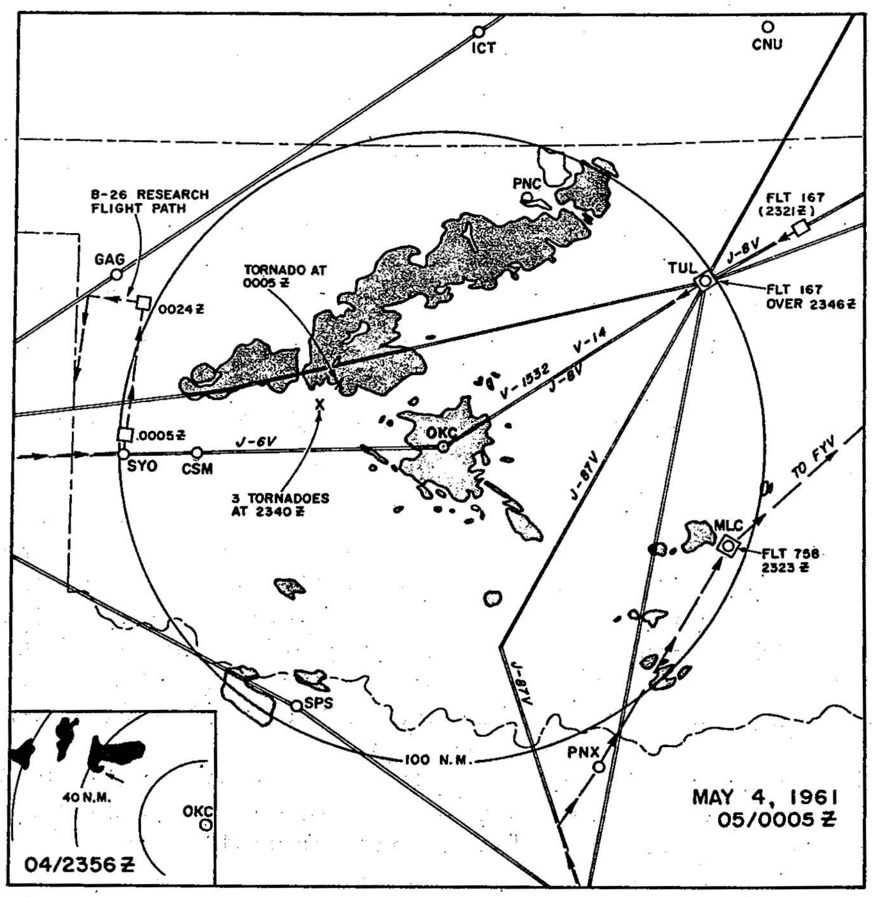

Figure 15.

N. DISCUSSION OF FIGURE 15

Time: 0005 GMT (5th)

Radar range: 100 miles

Antenna: 0°

Gain setting: 0 db.

On the 100-mi. range the details of the squall line NW of Oklahoma City are shown at a time close to the peak intensity. The line as a whole generated SE toward OKC but the individual cells all move NE. The three tornadoes 25 min. earlier were at the same echo edge as the 0005 GMT tornado in relation to this scope presentation. A figure-6 echo was associated with this later tornado, when 24-db. attenuation was added. (See inset, fig. 15, for this display at 2356 GMT.)

The NW-SE echo line through the radar site intensified during the next 90 min. and touched off a tornado visible to the W of Will Rogers Field. Those that occurred WNW of the field near Geary, Okla., have been studied in some detail by Hamilton [3], Ward [4] and Donaldson [5].

The Weather Bureau's B-26 at this time was flying a N-S oriented box pattern closer in to the line activity and at 0005 GMT had just turned the corner at Sayre (SYO) for the northbound leg. Some of the logged observations are pertinent in confirming the picture obtained on the WSR-57 radar at OKC.

B-26 RESEARCH FLIGHT NOTES

".... We have a good cell off on our right at about 20 miles distance contouring well, and it is about 60 degrees to the right of our nose...."

From flight observer's notes: "...13 miles north of Sayre we passed on the west side of a very large Cb which had a (radar) finger that extends back into the southwest. Underneath this finger you could actually see a protrusion of cloud extending down at an angle of about 30 degrees, very ragged, and looked like it might have been a funnel that had formed...." .... "At 1824 CST we were 40 north of SYO turning W...we could see the squall line on radar and it had an ENE-WSW orientation...."

Upon completion of two of the box patterns (0105 GMT, the B-26 was instructed by NSSP to return to AMA instead of proceeding to OKC because "this stuff was too severe for you to be flying back through".

Traffic control problems for this radar picture are in part, a continuation of figure 14 and have been discussed in sub-section M. One weather advisory was handled by ARTCC confirming the picture shown here.

0015: (Relay from MKC ARTCC to STL ARTCC) *Weather Bulletin. Radar picture from MKC. Southwest end 20 miles N of Clinton - Sherman* (CSM) *to NE of Ponca City* (PNC). *Eighty miles wide. Ponca City south is heaviest. Front edge is 40 miles W of Tulsa. Real severe. Tornado earlier. Will you give to* (Airline) *77?* Ans: *No.*

FTW ARTCC: *Fort Worth will give to* (Airline) *77.*

The 80-mi. width of the line referred to above must have been an all-inclusive interpretation of the activity which brought in the thunderstorms showing near OKC.

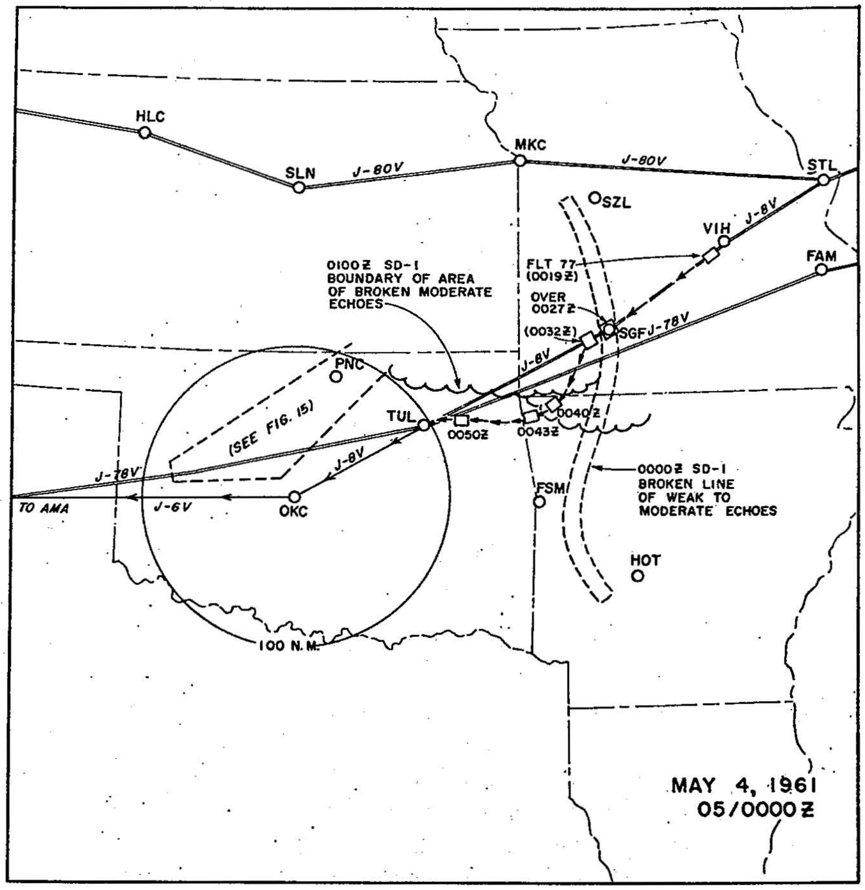

Figure 16.

O. DISCUSSION OF FIGURE 16

Time: 0000 GMT (5th)

No radar echoes have been reproduced in this figure since the traffic problems extend into areas beyond the 100-mi. range of figure 15.

Two SD-1 Rarep summaries define line and area developments for this time, and are so depicted geographically.

ST. LOUIS ARTCC CONTACTS

0019 GMT: (Airline) *77, flight level 310.*

0032 GMT: Discussion between MKC and STL Centers on radar information of severe weather. Weather bulletin of 0015 GMT given to (Airline) 77 and advised that J-8 looked best out of OKC. *"Near edge of echo just moving into OKC - but still west of TUL."*

0035 GMT (Airline) *77 over SGF at 0027Z, estimating TUL at :46.* (This flight a B-707 out of STL for LAX.)

0040 GMT: (Airline) *77 now south of J-8 to J-78. Wants to go J-78 to TUL.*

0043 GMT: (Airline) *77 requesting this route. TUL on J-8V to OKC, 6V to AMA, J-58V and* (garble) *to LAX. Due to weather, maintain 310.* (Unknown commenting on the thunderstorm as "just one great big cell".)

0050 GMT: (Airline) *77 detoured 20 miles S of new planned route.*

Good planning and advice on circumventing the heavy activity near OKC is evidenced in the contacts with Flight 77. However, more activity appeared to have developed in the area containing the "broken, moderate echoes" and additional detouring than planned was necessary before reaching TUL.

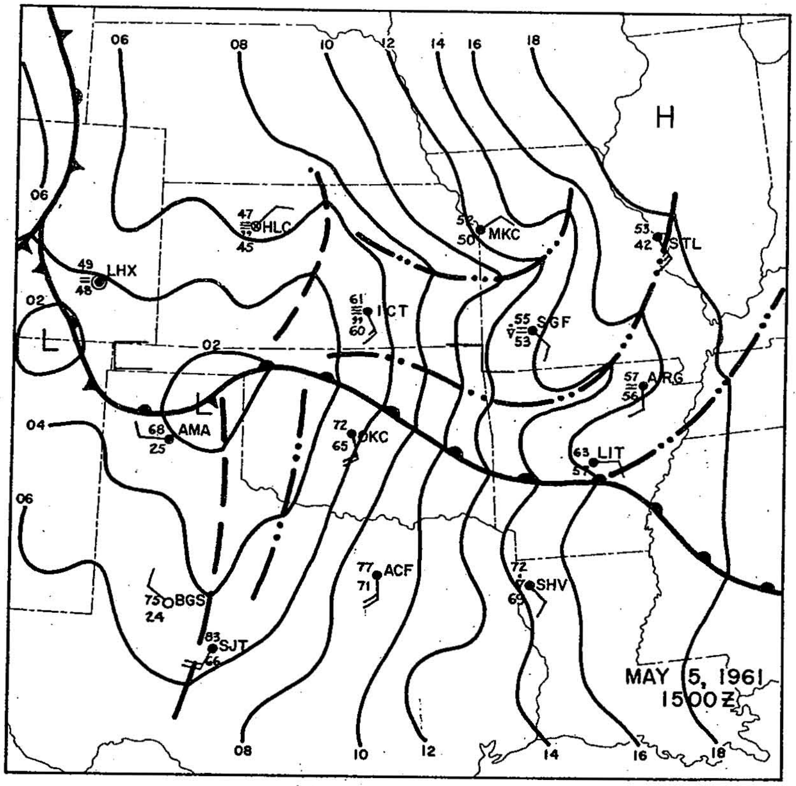

Figure 17.

V MAY 5 CASE STUDY

A. SYNOPTIC SITUATION (FIG. 17)

The surface analysis for the forenoon of the 5th was little changed from late afternoon on the 4th as will be seen by comparing it with figure 14. The principal low of the stationary front system was again in the Texas Panhandle. At 850 mb., the strong southerly flow of moist air continued at 1200 GMT, except for a turning of the winds to westerly in the AMA-BGS area. Above this level few changes were evident in the circulation from the previous day, with SW to WSW flow prevailing at all levels from 700 mb. to 200 mb. in the Oklahoma area at 1200 GMT. The tropopause was defined on the 5th at a higher altitude - 50,000 ft. The tropopause lowered about 10,000 ft. in the next 12 hrs. Maximum winds of 65 kt. occurred at 41,000 ft. but in the AMA-DDC area a jet stream was in evidence with core winds of 105 kt. from the SW. Stability conditions were also essentially the same as on the 4th.

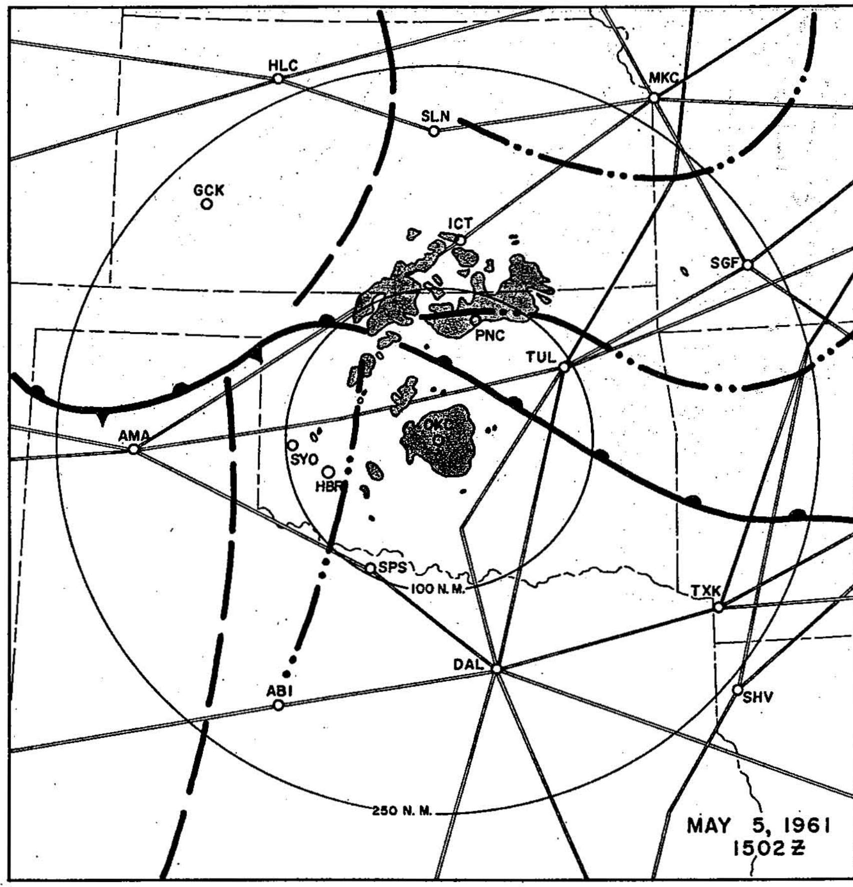

Figure 18.

B. DISCUSSION OF FIGURE 18

Time: 1502 GMT

Radar range: 250 miles

Antenna: 0°

Gain reduction: 6 db.

Most of the active cells shown at these settings are on the warm front surface. Although the instability line analyzed N of the TUL-PNC line does coincide with a large echo, there is little to suggest more than an area development at this time. The few scattered cells in the warm sector only vaguely fit the N-S instability line at 1500 GMT.

Severe Weather Forecast No. 184, issued at 1240 GMT and made valid until 1800 GMT outlines a severe thunderstorm area which blankets most of the echoes showing in figure 18. The complete forecast follows:

WW MKC FCST NR 184 051240Z

SVR TSTMS FCST

AREA 1 ...

A... ALG AND 60 MIS EITHER SIDE OF A LN FROM 40 MIS WNW HOBART OKLA 30 ENE PONCA CITY OKLA. VALID 051300Z TIL 1800Z.

B... A FEW SVR TSTMS WITH EXTRM TURBC HAIL 3/4 INCH SFC WND GUSTS SWLY 60 K. ISLTD CB TOPS TO 50 THSD.

C... TSTMS DVLPG ALG OLD SQLN SWRN OKLA EXPCD TO INTNSFY THIS MRNG WITH INDIVIDUAL CELLS MOVG NEWD 35 TO 40 K. THIS ACTVTY EXPCTD TO FURTHER INTNSFY BY ERLY AFTN REQUIRING FCST OF MORE SVR NATURE. CHAPPELL.

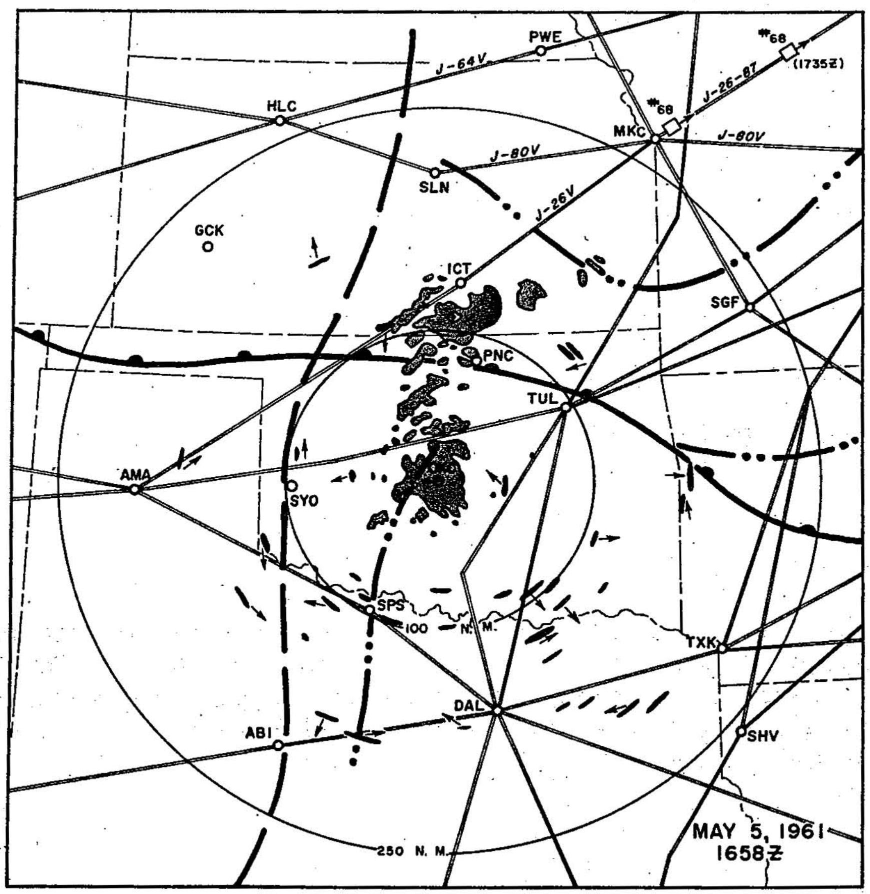

Figure 19.

C. DISCUSSION OF FIGURE 19

Time: 1658 GMT

Radar range: 250 miles

Antenna: 0°

Gain reduction: 12 db.

The warm front has moved to the north of TUL. Activity has increased on the warm front surface while more cells are tending to line up N-S in the warm sector. Both the ICT-AMA and TUL-AMA jet routes are posed with thunderstorm problems.

With an attenuation of 12 db. only the more important precipitation patterns are showing. This accounts for an apparent change in the display from large cells to many small ones. The radar room log noted 9 min. earlier that the echo bearing 233° from OKC at 54 mi. took 45 db. attenuation to knock off the scope - a small but very strong cell.

For the May 5 case study, all ARTCC traffic data were logged at the Kansas City Center except for two contacts from St. Louis. High altitude communications channels reserved for civil traffic contained little information in the STL area applicable to the study.

KANSAS CITY ARTCC CONTACTS

1730 GMT: (Airline) *68 over Kansas City at 390, Bradford :04, Joliet.*

1735 GMT: (Airline *68* (garble), *leaving 260 for 210.*

One minor weather factor may be inferred from these two contacts. In the early part of 1961, relatively few jet flights cruised as high as flight level 390 unless it was for weather reasons. This B-720 flight from Tucson to Chicago presumably planned a high altitude across the activity near Wichita, then started a quick descent after passing Kansas City.

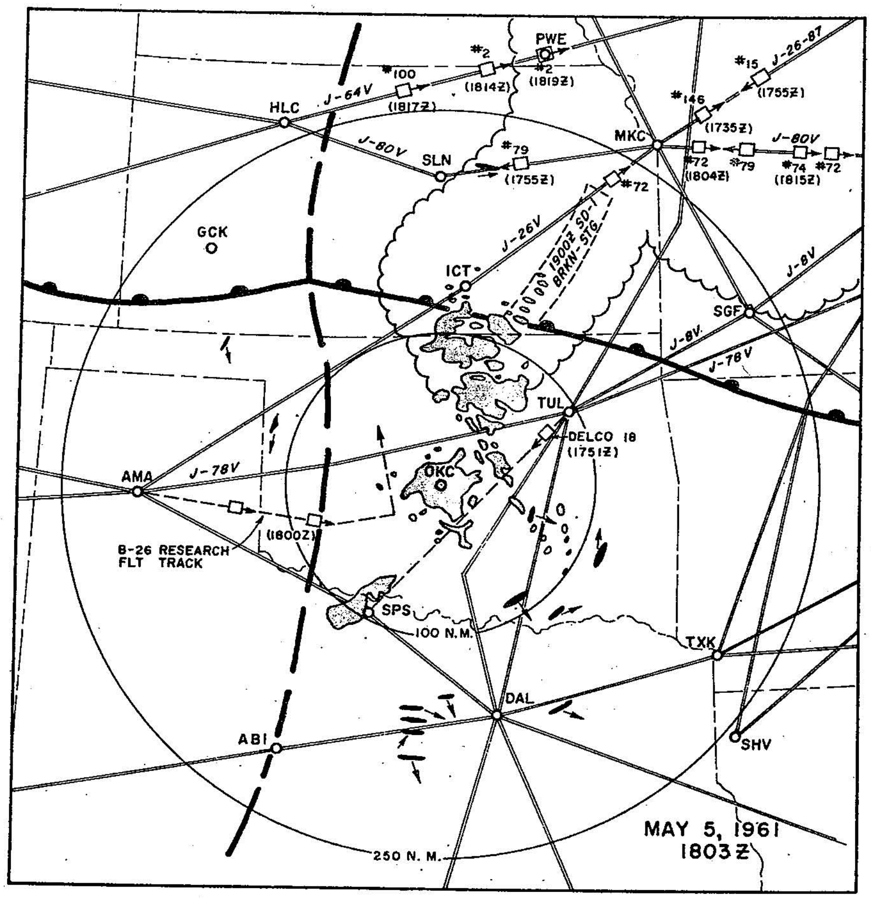

Figure 20.

D. DISCUSSION OF FIGURE 20

Time: 1803 GMT

Radar range: 250 miles

Antenna: 2° up

Gain reduction: 6 db.

With 2° elevation and 6 db. attenuation, the echoes in this display represent fairly high intensities of development. Ground clutter is also minimized around the radar site. Well defined line activity is showing from east of ICT into the large echo patterns inside the 100-mi. range mark. Note also the echo near Wichita Falls (SPS) which has blossomed in the past hour and would have formed in the central part of the instability line analyzed previously. The warm front has moved northward while the dry line discontinuity has progressed eastward into Oklahoma.

The B-26 research aircraft at this time was headed for a box pattern starting at Hobart and cornering at Anadarko, Fairview, and Woodworth. This was for the purpose of dry front data measurements.

Traffic contacts were in Kansas and Missouri beyond the range of the OKC radar or were involved in buildups still below the radar horizon for these distances. The 1900 GMT SD-1 Rarep Summary has been used to present the line and area developments. The scalloped boundaries represent an area of broken, strong echoes, with tops 35,000 to 38,000 ft.

KANSAS CITY ARTCC CONTACTS

Logged data are arranged chronologically by flights because of the number of aircraft involved.

1730 GMT: (Airline) *79, do you read?* (A B-707 flight out of St. Louis for Los Angeles.)

1746 GMT: (Airline) *79 over MKC 1245* (CDT), *310, Salina :05, HLC* (On J-80V airway).

1750 GMT: (MKC Center) *What about 370 to 330,* (Airline) *79 ?*

1755 GMT: (Airline) *79, we'll take any altitude up to 390.*

1737 GMT: (Airline) *146* (garble) *at 370, Bradford :14, go ahead.* (C-880 bound for Chicago out of Phoenix.)

1756 GMT: (Airline) *15, little rough at 5000. Would like to descend earlier.* (B-707 inbound to MKC from ORD on J-26, 87.)

1751 GMT: *DELCO 18 over TUL, direct to SPS.*

1804 GMT: (Airline) *72, MKC at* (garble) *370, St. Louis. Would like to get down.* (B-720 flight inbound to STL from LAX.)

1805 GMT: (Airline) *72, OK descend to flight level 250. Maintain 350 until* (garble). (On J-80V)

1806 GMT: (Unknown) *Any hail reported in this area?* (No response heard.)

1810 GMT: (From airline 72): *We showed three little cells. Appeared to be below us.*

1816 GMT: (Airline) *72. Just reached 250. Do you have anything more?*

1817 GMT: (Airline 72): *On instruments all the way down.*

1814 GMT: (Airline) 2: *We're going to detour south of course.* (B-707 on J-64V from LAX for IDL.)

1819 GMT: (Airline) *2: Over Pawnee* (PWE) *:19, estimate Bradford :53.*

1817 GMT: (Airline) *100: Reduced speed about 50 knots for a few minutes.* (B-707 on J-64V LAX to IDL.)

1830 GMT: (Airline) *100 has resumed speed now.*

These six airline flights were all involved in weather factors related to the traffic control problem. As evidence we have seen requests for higher altitudes, acknowledgment of rough air and detours, and a use of the higher flight levels to avoid turbulence.

Nearly all of these flights were conducted through the "broken, moderate" area defined in the 1900 GMT SD-1. Only one line development was recognized (as shown in SE Kansas), but it is apparent that the "broken" area required much use of radar in avoiding the worst turbulence.

Good confirmation of the echo near SPS was obtained from the research B-26 pilot remarks.

B-26 RESEARCH FLIGHT LOG EXCERPTS

(First position box E of AMA): "We have 70 miles to go to the Hobart omni. We're now showing a thunderstorm cell 40 degrees to the right of the nose and 110 miles away.... The cell seems to be in the vicinity of SPS."

(Near 1800 GMT position): "We are showing pretty good buildup now down in the vicinity of Wichita Falls (SPS). Looks like our line is already starting to form." ...(Later)... Encountered the moist air west of the Hobart omni...."

This last statement confirms the 1800 GMT position of the dry front.

Severe Weather Forecast No. 185 was issued by SELS at 1641 GMT for a valid period of 1800 to 0100 GMT.

WW MKC FCST NR 185 051641Z

AREA 1 ... TORNADO FCST

A ... ALG AND SIXTY MILES EITHER SD LN FROM 40 NW OF HOBART OKLA TO 20 SE OF CHANUTE KANS VALID FROM 1800Z TO 0100Z. PUB FCST ISSUED.

B ... NUMEROUS SVR TSTMS WITH TORNADOES AND HAIL UP TO THREE INCHES. EXTRM TURBC AND SFC WNDS SWLY GUSTS TO 70 KTS. SCTD CBS WITH MAX TOPS TO 60 THSD.

AREA 2 ... TORNADO AND SVR TSTM FCST

A ... ALG AND 150 MIS NE OF A LN FROM 40 W LINCOLN NEBR TO 70 SW HUTCHINSON KANS. VALID FROM 1800Z TO 0000Z. PUB FCST WIBIS.

B ... SCTD SVR TSTMS WITH HAIL UP TO $1\frac{1}{2}$ INCHES EXTRM TURBC AND SFC WNDS SWLY GUSTY TO 65 KTS WITH TORNADOES IN THE AREA SOUTH OF A LINE FROM 40 W SALINA KANS TO 40 NNE TOPEKA KANS. SCTD CBS TOPS TO 60 THSD.

AREA OF TSTMS EXPCD TO BE SVR IN THE EAST PORTIONS OF THE COUNTRY EAST OF THE PECOS RIVER AND THE NORTH PORTIONS OF NORTH TEXAS AND EXTREME SOUTHERN OKLAHOMA DURING MID AFTERNOON. FURTHER ADVRSYS WIBIS

WOOD

This advisory recognizes the increase in activity that is occurring in southeastern and northern Oklahoma and calls for more severe activity than called for in No. 184. Area 1 has also been extended NE into Kansas along the line of broken strong echoes defined in figure 20. A second tornado forecast zone (Area 2) has also been added to this forecast which includes part of southeastern Nebraska and western Iowa. This new zone coincides with the activity that has been giving trouble to the flights along J-64V and J-80V.

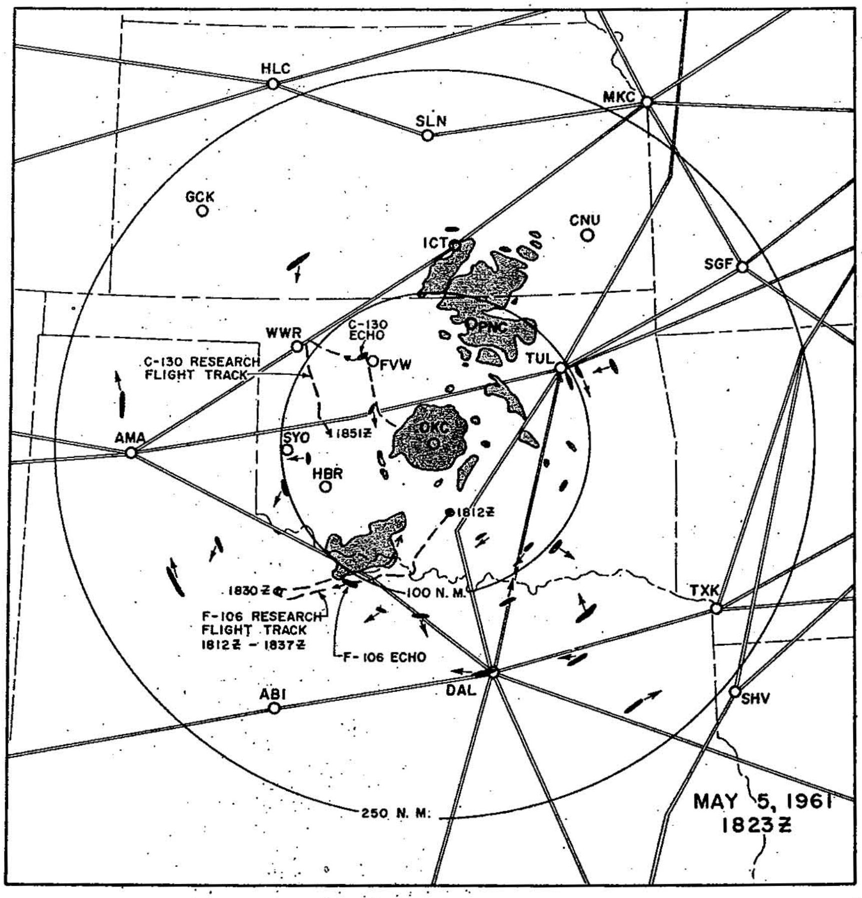

Figure 21.

E. DISCUSSION OF FIGURE 21

Time: 1823 GMT

Radar range: 250 miles

Antenna: 2° up

Gain setting: 0 db.

A pronounced increase in growth of the cells near ICT and at SPS have occurred in the 20 minutes since figure 20 even discounting the reduction of 6 db. attenuation.

This figure shows the flight path before, during, and after a penetration of a strong thunderstorm cell by an F-106 research aircraft. This path has been plotted from successive scope positions of echoes from this flight at 1-min. intervals. Flying at 40,000 ft., the track carried him on a fly-by at sub-sonic airspeed along the south side of the cell cluster, then a 180°

turn for the planned penetration at a speed of Mach 1.63. The key facts gained from this flight are presented in the pilot debriefing notes quoted here in part:

> "As I approached the storm, it was very well defined. It was puffy, glaringly white on top, but on the under side of these puffs, it was grayish. It looked to me like it was really boiling. The western edge of it was very clearly defined into a solid wall. As I got to within a few miles of the storm at my target altitude of 40, eye-balling the tops of them, it looked like they were around $44\frac{1}{2}$ or 45,000 feet. As I went into it, light precip. began almost immediately, and the cloud darkened as I went into it more. The heavy precip. started as soon as the cloud started getting real dark. This is where I think most of my turbulence was. I came out of this heavy turbulent area into a relatively smooth area. It was still raining, however. And then the turbulence increased again, and this area I think I got the hail. I could hear it hitting on the airplane, and the turbulence increased up to a level slightly less than my first area of turbulence. Keeping my attitude straight and level on my attitude indicator, I came out of the top of the storm, or the clouds, at $43\frac{1}{2}$. But up ahead of me there were higher clouds, which I went right back into, and then I pulled up--pulled up to about 47,000 feet, made a left turn, and I could see this general cloud picture very well. One of the interesting things, after I got on top at 46--between 46 and 47,000--the turbulence I would classify as almost moderate. I think any other airplane would probably have had difficulty up there. It was really bouncing me around. I was well on top of all the clouds when I experienced this moderate turbulence, on top. I would say I was 2,000 feet above any cloud."
>
> Question: Were you able to detect any build-up of turbulence?
>
> Answer: Yes, I think the turbulence was in direct proportion to the amount of precip., the heavier the precip., the heavier the turbulence.

Using data collected on this flight and others, Schumacher has published figures on gust velocities and frequencies [6].

The cell on the SW edge of the storm which was penetrated at 1832 GMT had blossomed on the radar to twice the diameter shown in figure 21 9 minutes earlier.

The severity of this cell can be judged by the radar room log noting that "42 db. did not knock out the echo". Height of the top of this storm estimated by the F-106 pilot was 5,000 ft. lower than measured from Fort Worth at the same time with ground radar.

The C-130 research aircraft operated at this time on the track shown in figure 21. Avoiding many smaller Cb on the climbout from OKC, he found a large anvil to the southwest and a "high, pretty solid line" east of the airport. In the first part of the box around Fairview (FVW) to Woodward (WWR), tops were well below the cruising altitude of 22,500 ft.

These observations correspond to the ground radar scope display, with no echoes in the FVW-WWR area and the line development east of OKC starting to separate from the ground clutter.

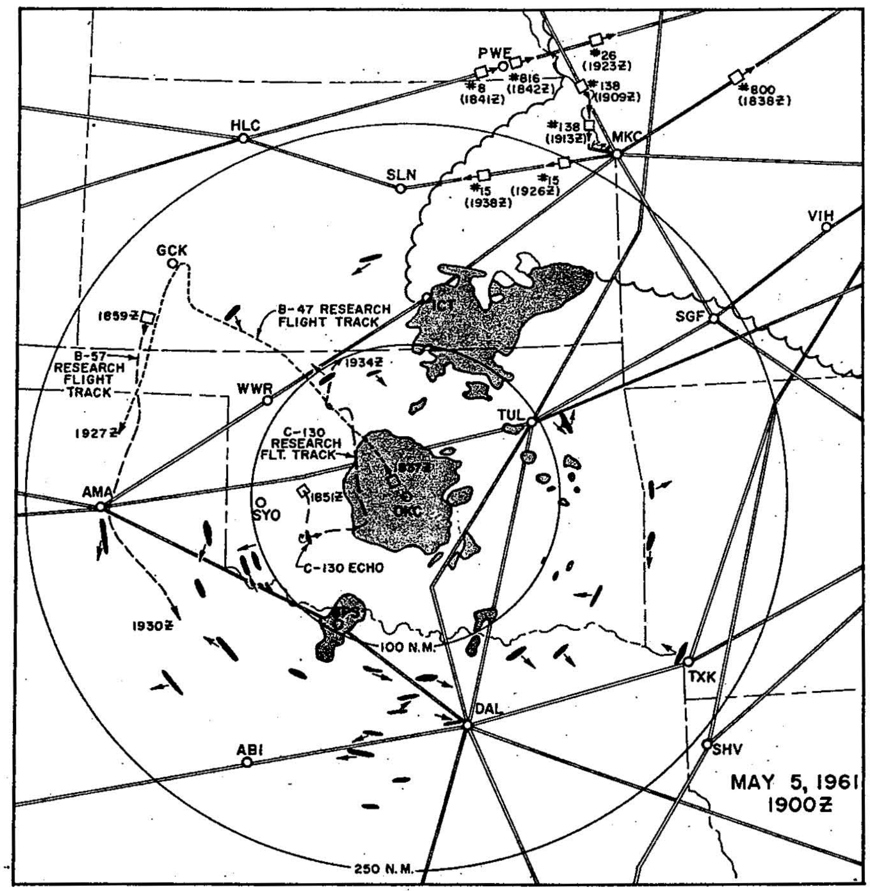

Figure 22.

F. DISCUSSION OF FIGURE 22

Time: 1900 GMT

Radar range: 250 miles

Antenna: 0°(0 db.)

Gain setting: normal (0 db.)

There is an apparent increase in size of some echoes between figure 21 and this figure, attributable to the change in antenna setting back to 0° elevation. However, increase in growth of thunderstorms east of Wichita has taken place and the strong development continues at SPS where the F-106 made its penetration.

Three of the research aircraft fleet are flying at this time. It is also apparent that there are many others in the air at the intermediate altitudes.

The air carrier traffic logged in the ARTCC contacts are involved in the weather patterns near ICT and northeast. The area around MKC set off with the scalloped boundaries in figure 22 is from the 2000 GMT Rarep Summary which defines the activity from broken, moderate echoes, tops to 35,000.

KANSAS CITY ARTCC CONTACTS

1838 GMT: (Airline) *800 at flight level 250* (B-707 outbound from MKC to ORD).

1842 GMT: (Airline) *816 over PWE :41 at 310, estimate Bradford* (garble). (DC-8 LAX to IDL.)

1845 GMT: (Airline) *816 requesting 350.*

1843 GMT: (Airline) *8 over PWE :42 at 330, estimate Bradford :17, O'Hare* (B-707 LAX to ORD).

1848 GMT: (From Flight 8) *How much separation do you have between* (Airline) *8 and* (Airline) *816 ?*

1909 GMT: (Airline) *138* (garble) *Victor 65, Victor 4 north.* (This is inbound low altitude airway from STJ to MKC and flight 138 is C-880 from LAX for MKC.)

1913 GMT: (Airline) *138, we just turned off one engine. Need your help to keep clear of thunderstorms and would like a simple* (descent) *clearance.*

1914 GMT: (Airline) *26 over PWE :14 at 330, estimating JOT.* (B-707 LAX-ORD.)

1923 GMT: (Airline) *26, lots of static here.*

1926 GMT: (Airline) *15 requesting 330 or 350, metro reasons, when available.*

1938 GMT: (Airline) *15, if 350 not available, will take 370, metro.*

Again six flights are connected to weather-generated control problems similar to those summarized in sub-section D. Plans at the higher flight levels and requests for clearance to higher altitudes point up the concern to stay above the activity as much as possible. (Detouring is generally less extensive with radar at these levels than at lower altitudes.) The problem facing Flight 138 on three engines emphasizes the added complexity of aircraft control during descent through thunderstorm conditions.

C-130 RESEARCH FLIGHT DATA

Observations by the flight meteorologist during the portion of the flight shown in figure 22 verify the presence of the dry front from Hobart northward. By this time the winds above 25,000 ft. were increasing also as the jet stream moved closer to the area. The effect on the buildups W and NW of OKC from the shear and introduction of dry air was to produce clouds that "...would build up to about 30,000 ft. in very narrow turrets and blow off...there was no support from underneath."

B-47 RESEARCH FLIGHT LOG DATA

Figure 22 includes track of the ASD B-47 from near OKC to north of AMA flown at 28,000 to 32,000 ft. This track was constructed from the flight log which contained a few Doppler wind readings. These winds agreed closely with the rawins for Dodge City and Amarillo. Seven minutes beyond the GCK turn (at 1914 GMT) a small line of echoes was noted at 175 mi. on the aircraft radar, corresponding to the hint of a line bearing 010° from OKC at 60-80 mi.

B-57 RESEARCH FLIGHT NOTES

The path constructed from the flight log shows the first portion of a diamond pattern flown for data gathering and cloud photography. Flight altitude on this segment was 39,000 ft. Readouts of ambient air temperature and winds at 2-min. intervals have been analyzed by NSSP. This analysis reveals a maximum horizontal temperature gradient of 3.5° C. in 14 mi. occurring at the 1909 GMT position (just south of the Oklahoma-Texas border). Warmest temperatures were on the north side.

At 1832 GMT, the SELS office at Kansas City issued Severe Weather Forecast No. 186, with a beginning valid time of 1900 GMT.

WW MKC FCST NR 186 051830Z

AREA ONE ... TORNADO FCST

A ... ALG AND 120 MIS N OF A LN FM 20 WSW MINERAL WELLS TEX TO 65 MIS S OF FT SMITH ARK VALID FM 1900Z TO 0100Z. PUB FCST ISSUED.

B ... SCTD SVR TSTMS WITH HAIL UP TO TWO INCHES EXTRM TURBC AND SFC WNDS SWLY GUSTS TO 65 K AND ONE OR TWO TORNADOES. SCTD CBS TOPS TO 60 THSD. WOOD.

The tornado forecast area here is relocated 120 miles SE of the box defined in WW No. 185. The new tornado zone includes the large development at SPS and the scattered echoes in southern and eastern Oklahoma plus the areas into which this activity would move northeastward.

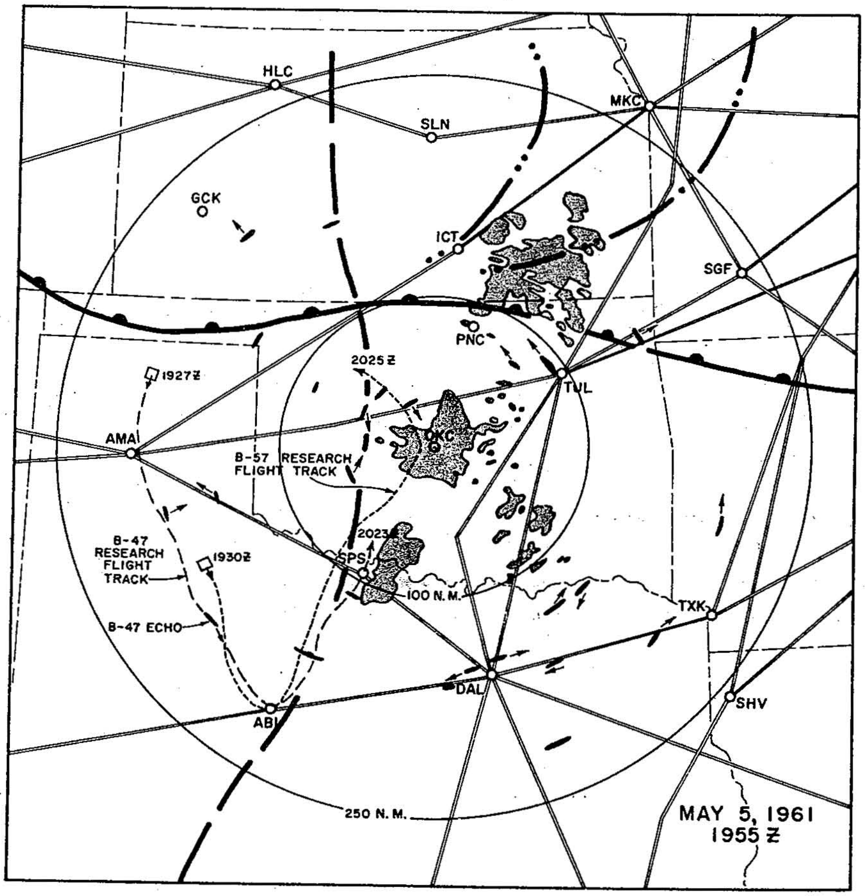
HLC
SLN
MKC
GCK
ICT
SGF
PNC
2025Z
TUL
1927Z
AMA
OKC
B-57 RESEARCH FLIGHT TRACK
2023Z
B-47 RESEARCH FLIGHT TRACK
1930Z
SPS
100 N.M.
B-47 ECHO
TXK
DAL
SHV
ABI
250 N.M.
MAY 5, 1961
1955Z

Figure 23.

G. DISCUSSION OF FIGURE 23

Time: 1955 GMT

Radar range: 250 miles

Antenna: 0°

Gain setting: normal (0 db.)

Except for the SPS storm — now over 2 hours old — no well defined line activity shows on the scope. A second major area is still going strong to the northeast of the TUL, PNC, ICT line. The SPS cell is producing $2\frac{1}{2}$ inch hailstones at this time at SPS. Individual cells show here in the periphery of the radar site ground clutter, and there has been an increase in activity southeast of OKC.

The easternmost of the two instability lines has good radar confirmation on its lower end and the activity in southeast Kansas fits the surface warm front analysis well. The dry front has continued eastward at about 30 kt. A continuation of the B-47 and B-57 research flight tracks from the previous figure nearly completes the diamond pattern flown by these aircraft. Path of the B-47 is traced from the radar films; the flight log was used in constructing the B-57 track.

No data were processed from this segment of the B-47 flight which were pertinent to the study.

B-57 RESEARCH FLIGHT NOTES

The NSSP analysis discussed in the previous sub-section revealed a wind maximum for the flight at 39,000 ft. of 110 kt. near ABI. This coincides both in speed and position with the maximum wind as shown on the 200-mb. analysis for 06/0000 GMT. Forty-five mi. behind this point the Doppler radar had measured the wind 30 kt. lighter for a shear of about 0.7 kt./mi. A lesser wind maximum was crossed just south of OKC.

Temperature changes over this segment of the flight were not as pronounced as before. Debriefing notes mentioned the squall line from "just east of ABI on up towards SPS and across the Red River area". Neither the SD-1 Rarep Summary nor this scope display confirms a squall line south of the large SPS echo. The south end of the line must have been made up of shower cells too weak to be picked up by the FTW or OKC ground radars. The dry line would be the natural trigger for a development here.

Tops of the squall line near SPS were estimated by the flight meteorologist at between 50,000 and 55,000 ft. Figure 24a is a photograph taken from the B-57 looking northeast toward the south end of the squall line near SPS.

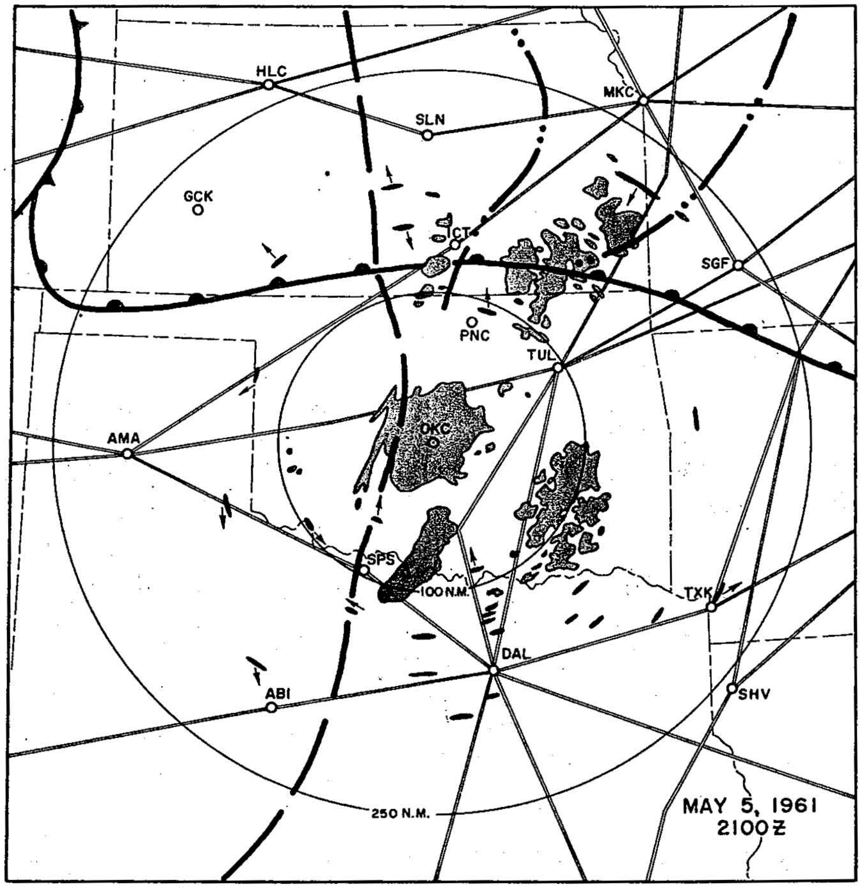

Figure 24.

H. DISCUSSION OF FIGURE 24

Time: 2100 GMT

Radar range: 250 miles

Antenna: 0°

Gain setting: normal (0 db.)

This midafternoon scope display typifies the rapid development that can occur in 1 hour when the stage is set properly with the right conditions of moisture, stability, and circulation.

The elongated echo line from northwest to southwest of OKC is a radar "thin line" not usually directly associated with thunderstorms [7] and [8]. The large and persistent line near SPS has stretched downwind toward OKC. In southeast Oklahoma growth and consolidation of cells has occurred and a line is starting to form toward DAL. This development triggered a destructive tornado 3 hours later. To the north and northeast of the radar site additional cells have appeared on both sides of the surface warm front. The instability line near ICT now has good radar confirmation on its south end.

Several important jet airways are either crossed by thunderstorms at 2100 GMT or are threatened in the next few hours. Similar traffic control problems face the ARTC Centers in the handling of aircraft operating in the intermediate and lower altitudes. Tapes of traffic control contacts were not, unfortunately, logged for this period.

The B-57 research aircraft completed the diamond pattern previously discussed, and between 2104 and 2118 GMT circumnavigation of buildups was conducted near Ponca City (PNC) at 44,000 ft. Figures 24b, and 24c are photographs of some of the Cb in this area. Highest tops were reported here at 45,000 ft. Figure 24c was taken after crossing the cloud.

Figure 24a.- View from B-57 at 40,000 ft. approaching south end of buildups near SPS (looking NE). Cloud tops were estimated between 50,000 and 55,000 ft. Sharp break-off in lower cumulus is probably coincident with dry front depicted in figure 24.

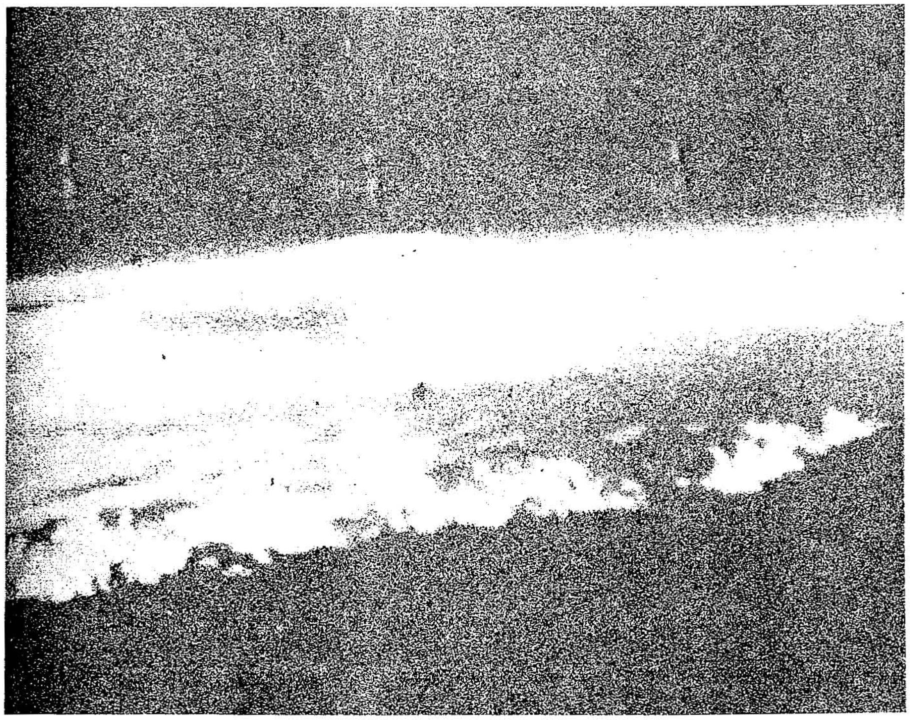

Figure 24b.- View from 44,000 ft. approaching west side of buildup near PNC which is part of a new line of development. Sharp break-off in lower cumulus in foreground is probably coincident with dry front depicted in figure 24. Tops of the Cb were measured a few minutes later as 45,000 ft. by the B-57.

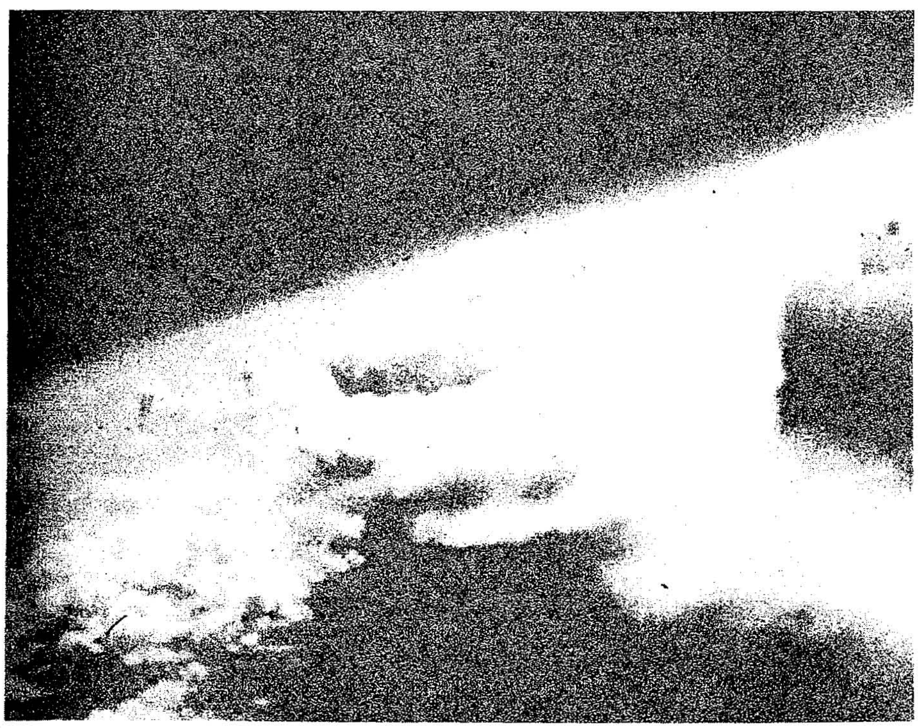

Figure 24c.- The shelf or anvil cloud of same Cb (fig. 24b) is just below aircraft which has crossed over line from opposite side. View is toward WSW.

VI. DETERMINATION OF THE SEVERE WEATHER AREAS

A. GENERAL

The use of the term "severe weather" in this study has been restricted to those elements generated by thunderstorms that are considered hazards to aircraft operation and control between takeoff and touchdown. These are:

(a) Turbulence

(b) Hail

(c) Tornadoes

(d) Icing

(e) Precipitation other than hail

(f) Lightning

(g) Clouds

Items (d) through (g) above will not be evaluated in detail in this report, but are factors that must be considered in a broad study of weather effects on aviation [9]. Icing in thunderstorm zones is a hazard to only a very small segment of aviation operations under positive ground control. Snow, rain, and soft hail represent hazards only in the *control* of air traffic when intense enough to produce clutter on the ARTC scopes. Lightning is a factor on rare occasions only as it may temporarily reduce visual acuity of pilot personnel. The presence of clouds represents a safety factor to consider in ground-controlled enroute aircraft operations only in the very remote event of partial or total electrical and hydraulic system failure.

Severe weather may also be generated from non-thunderstorm sources. Foremost among these considerations is *Clear Air Turbulence*. An evaluation of this operating problem is not within the scope of this study, but it certainly deserves top rank consideration in the ultimate design of any automatic air traffic control computer system. Studies of this weather element have already been undertaken by the contractor, [10], [11], and others, but much more research, particularly in the development of sensing devices, is required before this element may be used as input data.

B. THE USE OF GROUND RADAR

At the present time there appears to be no equal to ground radar as the system to be employed in determining the three dimensions of thunderstorm activity. In the case studies of Section IV and V most of the data related to turbo-jet operations. In any system of control of air traffic, evaluation of the method of data acquisition must also be concerned with the conduct of flights below 25,000 ft. From the nature of thunderstorm structure operating hazards are not much different below 25,000 ft. than they are above this altitude, except in the matter of frequency. Radar used as a data gathering system fulfills not only the needs of turbo-jet flights but also satifies the piston aircraft requirements.

1. WSR-57 Radars

The WSR-57 radar as employed at Will Rogers Field is an excellent tool for providing PPI storm data. It is designed for the primary purpose of weather detection. The step gain feature in the hands of a trained radar meteorologist is essential in separating the important cores from the echoes returned by light precipitation and less turbulent zones.

Accuracy of positioning of storm cells has been documented in Section IV and V from both surface and aircraft observations. (See discussion of figs. 7, 8, 9, 10, 12, 14, 20, and 21.) To obtain the same high degree of reliability as was demonstrated during the two case studies, all radars employed routinely for use in conjunction with a computer system must:

a. Be kept tuned to top efficiency by proper maintenance.

b. Have reflectivity calibrated at reasonably frequent intervals.

2. Limits of Range

In the discussion of figures 7, 8, and 20, specific points were made on the inability of the radar to pick up returns from thunderstorms at a distance. The approximate line-of-sight limitation can lead to voids in the radar echo input data if too great a distance separates the radar locations. The control problem would be particularly critical for aircraft operation in the intermediate and low altitude ranges. Until the areas of forecasted thunderstorms can be narrowed down by improvements in the art, the growth of squall lines or new cells in the distant ranges will impose a problem of detecting developments in the incipient stages.

3. Vertical Dimensions

The PPI radar display will probably do an adequate job of establishing airway weather blocks in low and intermediate altitude operations. However, in turbojet operations, much usable airspace will be blocked off if a PPI presentation at 0° antenna setting is projected upward through all flight levels. The vertical dimension of the thunderstorms must be fed into the control computer if efficient use of airspace is to be made. At present there are only two methods of measuring the third dimension -- by aircraft, and by vertically scanning radars (or the CAPPI method). The first is impractical because of scarcity of reports and a communications problem. The second method is a practicable one but requires further refinement.

No direct RHI data were evaluated in this study, although comparisons were drawn from aircraft observations and ground radar logs (See discussion of fig. 21). It is apparent that errors of significant magnitude are inherent in the interpretation of echo heights measured at ranges in excess of 100 mi. Studies by Donaldson of the May 4 case [5], observations from jet aircraft listed by Beckwith [12], and others cite additional discrepancies. Jordan has reviewed the errors in certain RHI data at length [13].

Until the echo height data can be made more reliable at ranges of over 100 mi., the severe weather zones established by part of the PPI displays will probably have to govern the airspace block for most turbojet flight levels.

4. ARTC Radars

The radars designed for traffic control and flight following use circular polarization to eliminate most of the echoes from the heaviest precipitation cores. Although linear polarization is generally employed with these sets when storm echoes do not interfere with the radar's primary function, it does not seem practicable to utilize these facilities for the meteorological function. This reasoning carries more validity when we consider the need to have a radar meteorologist available to tie together the storm development, forecasts, and the scope picture.

C. THE USE OF SURFACE OBSERVATIONS AND ANALYSES

Only when thunderstorms have reached the squall line stage is there some consistency in the reporting of the development through the normal synoptic scale observational network. This reporting deficiency is not a weakness in the observing technique, but is related to the density of observing stations. Even in areas where the hourly and synoptic reporting station density is higher than the average for the United States, there are occasions when extensive squall lines go unreported for periods greater than the life of the component cells. One such example is pointed out in the discussion of figure 14, another is documented in reference [14]. With the aid of mesoscale networks, the true ground picture of the thunderstorm or squall line is possible. Even here, however, the lag in communications, as presently constituted, precludes the quick analysis for computer input. Mesoscale surface reporting coupled with instant communications would also not provide the kind of data needed to establish the severe weather zones aloft, unless backed up by radar.

The surface synoptic analysis provides little information that can be utilized for anticipating the details of thunderstorm developments for periods of less than 2 hours, even if fast computer techniques were available. The two case studies provide good examples, which have been pointed out, of how imperfectly the area and line thunderstorm developments fit the classical surface synoptic patterns. Improvements in analyses and forecasting of thunderstorms made in recent years show a trend toward greater use of upper air data. This, of course, complicates the design of the elaborate systems of computers and communications such as visualized by the Common Aviation Weather Systems program for 1965 or later [15].

D. AIRCRAFT REPORTS

At best, pilot reports from aircraft operating in or near severe weather areas should be considered as supplementary to data gathered by ground radar or other means. Even if communications were instantaneous, the subjective observations of cloud structure or flight conditions are either too general if describing the broad picture or too limited in scope if defining small details.

Flights conducted for extensive periods in old anvils or between cloud layers cannot give an adequate report of the severe weather zones except to confirm from their radars what may already be known from the ground sets. The severe line developments automatically reduce the number of usable pilot reports by the preplanning practiced by most operators to give the area a wide berth on alternate routes. If coupled to the computers by instantaneous communications channels, aircraft reports may be utilized to define tops or navigable corridors. This supplemental data would complete the definition of the usable airspace in those areas beyond the capability of PPI or RHI displays on ground radars.

E. SFERICS

The application of this system to the collecting of thunderstorm data for computer input was not evaluated in this study. A sferics network has a distinct range advantage over radar, but this is more than offset by the inability to extract usable data for defining in sufficient detail the incipient severe storm zones. Sferics may have greater application in the future when further research has uncovered the role of atmospheric electricity in the development of thunderstorms.

F. PHOTOGRAPHS FROM HIGH ALTITUDES

Conventional methods of producing photographs of cloud systems from high altitudes have a built-in delay of proportions that eliminate the possible application of U-2 airplane or satellite observations. If, however, techniques can be perfected for immediately transmitting to the operational users by facsimile, the pictures being taken, these are avenues that should be pursued in further research. Cloud photographs by themselves would not suffice to establish the areas of severe weather, since great canopies of blow-off frequently mask the cloud towers that concern the traffic controller. Studies by Fujita [16] and Blackmer [17] have shown what the relationship is between the radar cores and the high altitude cloud depiction. Photographic observations have their greatest potentialities in the regions where surface reporting and radar networks are sparse.

VII. THE AIRSPACE WEATHER BLOCK

The easiest approach to establishing tolerances for automatic traffic control would be always to give severe weather zones a wide detour of both track and altitude. This approach, however, would be a waste of valuable airspace and time in many situations.

A. AIRBORNE RADAR

The FAA special regulation SR-436A requires an operating radar set on nearly every category of transport aircraft. It seems reasonable to assume that the aircraft scope display will be utilized as an arm to the ground control radars for close-in navigation. Procedures have been developed by the aircraft operators [12], [18] based on long experience which permit a minimum amount of detouring of thunderstorms without increasing the exposure to turbulence, hail, and tornadoes.

The flight condition portrayed in figure 9b is one in which detouring of the core on the right at closer than the 20 mi. usually recommended, is done without undue risk, as long as the flight clears the outer edge of the blow-off. The same thunderstorm structure obscured by a dense cirrus layer would involve instrument flight. Detouring the core under these conditions with less than 20 mi. separation would be done against recommended operating practice.

In over-the-top navigation, many line squall penetrations have been made safely and comfortably on instruments with radar through the saddles between tops, but using the 20-mi. rule. In contrast is the condition experienced by the F-106 pilot quoted on page 47 where moderate to severe turbulence was encountered in the clear air above a rapidly growing cumulonimbus.

B. MONITORING THE COMPLETE RADAR PICTURE

In the more severe thunderstorm developments a provision should be made in the air traffic control system for filling in details of the storm with feedback information from aircraft radars and observations. This provision should initially assist in completing the picture in the areas swept by the ground radars beyond 200 mi. Even more important is the necessity of evaluating in the computer the time sequence of ground radar echo dimensions, intensity, and movement. Only with this kind of data can the programming of aircraft traffic realize maximum utilization of airspace. Waiting until an airway is cleared of a severe storm area would be much less efficient than being able to clear the conflict predictor over the airway before the airspace was actually vacated by the storm. A study by Nagle [19] associating certain radar echo characteristics with high altitude aircraft accidents offers encouragement to further research which could lead to highly useful data for air traffic control computers.

VIII. FORECASTS AND COMMUNICATIONS

A. 30-MINUTE FORECASTS

With radar data being sequenced into a traffic control computer, a lead time of 20 to 30 min. is sufficient to handle the programming of flight plans and flight following information. The forecast requirement for such a short interval thus resolves itself pretty much into a time projection of continuously updated radar scope information. Forecasts of thunderstorm activity based on the dynamics of the meteorological conditions play a relatively minor part in the solution of the immediate traffic control problem.

B. TWO-HOUR FORECASTS

Forecasts of 2 to 3 hours are, however, required for both the flight planning function at point of origination and for pre-planning the flight control load on certain airway segments. For forecasts of this length, the current radar data will contribute little to the required accuracy. A fairly comprehensive synoptic analysis of available surface and upper air data is required as background here.

C. SIX-TO EIGHT-HOUR FORECASTS

The Severe Weather Forecast (WW) issued by the U. S. Weather Bureau's SELS Center falls into this forecast requirement. As related to this study, the primary use made of the area outlook of thunderstorm activity is by aircraft operators at time of flight planning and for preparing pre-release messages.

Flights operating for non-stop distances of 800 to 1000 miles or more are often planned over such routes as to completely by-pass a forecasted area of heavy thunderstorm activity. The WWs or their equivalents are of great value for such applications, and it is probable that they will continue to be so used. Advance notice of extensive thunderstorm activity will also be valuable to the traffic control function for general planning purposes, for programming maintenance shutdowns, and other activities.

1. Accuracy of WW Forecasts

A validation of the forecast areas of activity called for in the Severe Weather Forecasts against the scope displays discussed in Section IV and V discloses the following:

(a) Most of the important thunderstorm areas and squall lines fall within the forecasted zones.

(b) Within a large portion of the forecast severe weather boundaries there was no radar echo verification.

(c) Forecast movement of specific line developments showed good verification in 2 out of 3 cases.

This verification is biased against the forecaster because the radar is not displaying some of the weaker activity that would qualify as validating data. It is also recognized that the forecaster is handicapped by lack of obsertional tools and that a better knowledge of thunderstorm dynamics must evolve from further research.

D. RAREP SUMMARIES (SD-1)

The standard method of transmitting radar echo data from many sites by word description has the usual drawbacks that any manual system faces in combination with teletype channels. In Section V where reference was made to the SD-1s for verifying the ARTC contacts involving weather, we have quite pointedly used the SD-1 for the *following* hour as the *current* picture. This method of collecting radar composites is obviously not suited for transmission as input to computers. Further discrepancies have been noted between the actual radar picture and the radar summaries received by facsimile 2 to 3 hours after the fact.

IX. CONVERTING THE STORM DATA FOR COMPUTER USE

The most direct approach to obtaining information on the volumes of airspace occupied by severe weather and converting it quickly for computer use is through the use of radar. The advantages of this tool over other methods should be apparent after reviewing the evidence presented in this study.

Several methods have been developed for converting the radar data into digital form suitable for handling by the traffic control computer. Others are in the stage of refinement which will permit nearly instantaneous input of the echo information without the necessity of relying on slow photographic or facsimile methods. A recent review by Kessler [20] points to at least two systems that offer promise of early solution to this conversion problem. The CAPPI echo display developed and refined by the McGill University group [21] may be a workable solution to feeding the three-dimensional data to the computer. Sweeney [22] and Collis [23] have outlined other methods of radar data processing.

Any of the systems which digitize the radar return through a grid form should use a pattern not coarser than the equivalent of 5-mi. squares, or important details of route availability are likely to be lost. The final design should also incorporate a facility for adding information obtained from other sources such as feedback from aircraft or scope data from adjacent radars.

X. RECOMMENDATIONS

The 45-year totals of tornado occurrences shown in figure 25a have been selected as representative of the relative frequency with which ARTC centers are faced with weather-dominated control problems which involve the enroute turbulence risks. The siting of WSR-57 radars as mapped in figure 25b indicates that relatively few additions would be required to provide the weather radar coverage necessary for backing up an automatic air traffic control system in the United States (See Recommendations 2 and 3 below). Circles for each site in figure 25b are drawn for 100 mi. ranges in keeping with the distance limit for accurate RHI data. Some of the uncovered areas shown on this map are within the sweep ranges of other types of radars, but these are not necessarily compatible with the characteristics of the WSR-57 sets.

For a summarization of the main points of this and preceding sections the following recommendations are made:

1. It is recommended that the WSR-57 radar with the step gain feature be considered as the primary instrument for collecting severe storm input data.

2. To provide the fullest coverage of severe storm occurrences the existing WSR-57 radar network should be expanded initially into western Kansas, eastern Nebraska, eastern South Dakota, and the central portions of Mississippi, Alabama, and Georgia.

3. Research should be intensified in the RHI application of radar to improve accuracy beyond the 100-mi. range.

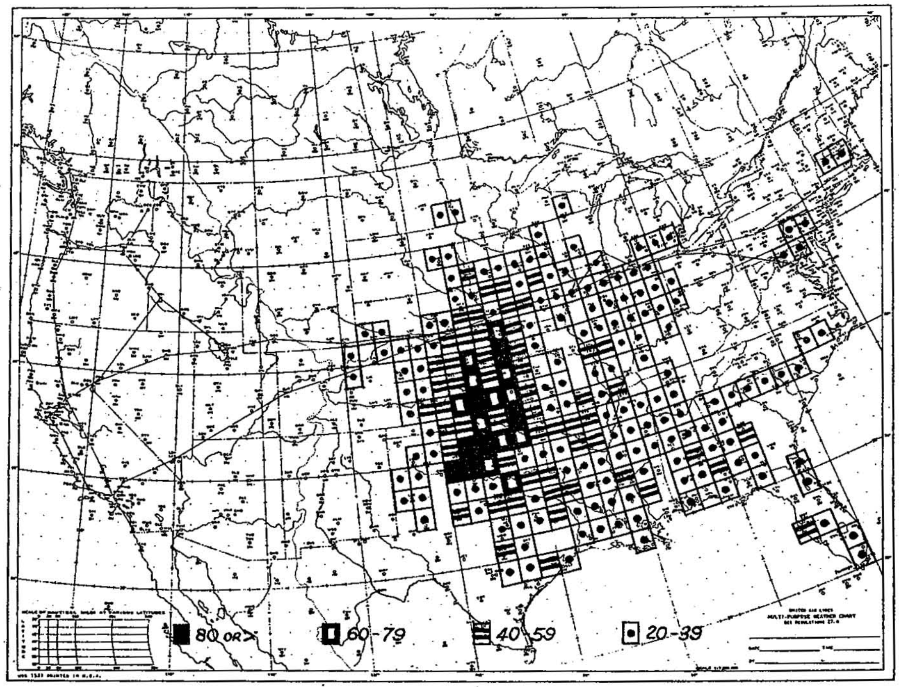

Figure 25a.- Tornado frequency by 1 degree squares based on 45 years of data 1916-1961. (After U. S. Weather Bureau).

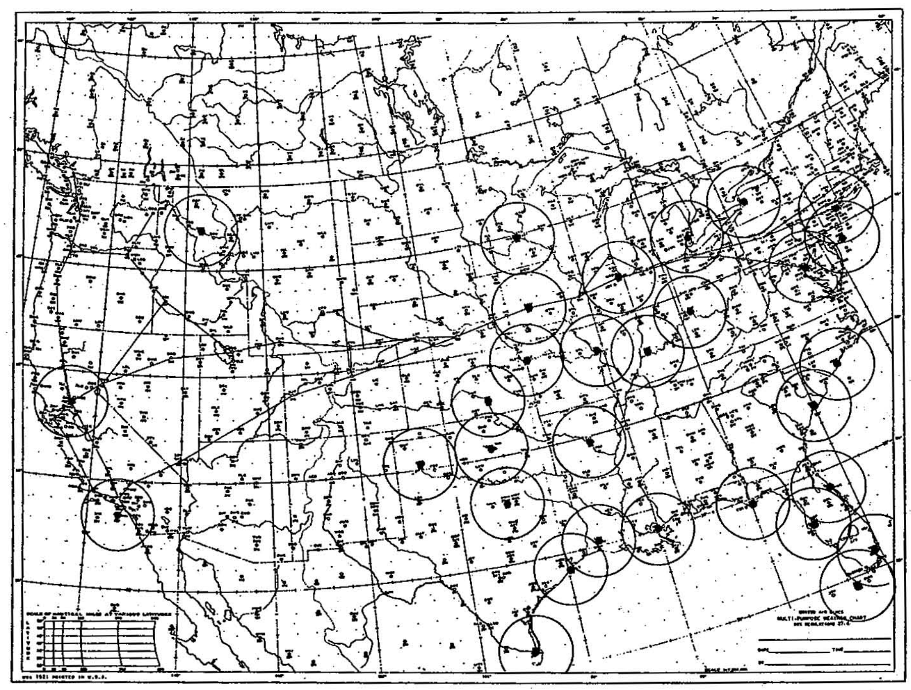

Figure 25b.- Locations of WSR-57 radar installations as of July 1962. (Catalina and Chicago scheduled for fall of 1962.) Circles are scaled for 100-mile sweep radius.

4. To improve the accuracy of the important planning forecasts in the 2 to 8-hour range it is recommended that the radiosonde network be expanded both in number of stations and frequency of runs. Meso-scale observation networks should also be extended to assist in the forecasts required for periods of 2 hours or longer. Frequency of radiosonde runs should be upped to four per day, or more often for serial soundings or test cases. Density of such stations should be increased initially in the NSSP field test area.

5. Finally, there appears to be strong justification, based on the needs of aviation alone, for continuing the intensive research as organized under the National Severe Storms Project.

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